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CUBIC CORPORATION

JPL NO. 9950 – 1007

TR/209-3
6 February 1985

MOBILE ANTENNA AND
BEAM POINTING STUDIES FOR
SATELLITE MOBILE COMMUNICATIONS

FINAL REPORT

JPL CONTRACT 956691

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration, under contract NAS7-100.

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ABSTRACT

This report is a supplement to the Cubic Interim Report TR/209-1 entitled "Trade-off Between Land Vehicle Antenna Cost and Gain for Satellite Mobile Communications." This report contains further studies for design and cost reduction of the 1x4 array and the conformal array. Costs and designs of several antenna pointing techniques are reported.

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TABLE OF CONTENTS

1.0 SUMMARY

The cost and performance for the mechanically scanned 1x4 planar array and mechanically scanned conformal array were developed further. Several methods for accomplishing the antenna pointing were investigated in depth. The performance and costs are summarized in Tables 1.0-1 and 1.0-2.

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TABLE 1.0-1. MSAT-X VEHICLE ANTENNA CANDIDATE CONCEPTS

No.	Antenna Type	Size		Cost				Technical Features				Development Time			Comments
		Height	Base	Development		Manufacturer		Gain	Two Satellite Isolation	Polarization Isolation	Drop Off Rate to 0°	B. B.	Prototype	Date Available	
				B. B.	* Prototype	Lots of 100	Lots of 10,000								
1	Portable Non-Tracking	N/A													
2	Mechanically Tracking Microstrip Patch Tilted Linear Array	6.5"	33"	125K	100K	1K	0.5K	10dB	15dB	3dB	8dB	8 months	8 months		Gyro aided Monopulse Tracking System
3	Mechanically Tracking Conformal Phased Array	3.0"	36"	150K	125K	1.6K	0.95K	9 dB	20dB		6dB	12 months	10 months		Gyro Aided Monopulse Tracking System
4	Current Technology Electronically Tracking Conformal Phased Array	2.5"	38"	200K	150K	3.6K	2.9K	9dB	20dB		6dB	16 months	16 months		Not studied within the scope of this report.
5	Advanced Technology Electronically Tracking Conformal Phased Array	N/A													

B.B. = Breadboard

*Assume B.B. effort precedes prototype.

TABLE 1.0-2

	POINTING SYSTEM			
	GYRO AIDED MONOPULSE	COMPASS	AGC	AGC COMPASS
Acquisition Time				
Typical	15.1 sec	5.1 sec	16.4 sec	6.3 sec
Minimum	0	0	16.4	1.3 sec
Reacquisition Time				
Typical	5 sec	0 sec	5 sec	1.3 sec
Minimum	0	0	0	0
Tracking				
Rate	36°/sec	36°/sec	36°/sec	36°/sec
Acceleration	24°/sec	24°/sec	24°/sec	24°/sec
Accuracy - Peak	2°	45°	10°	10°
Accuracy - Typ.	0.5°	7.5°	6°	6°
Robustness in Fading and Shadowing	Excellent	Excellent	Poor	Fair
Other Factors Limiting Performance		Magnetic Declination		
Antenna Type Applicability (mechanical scan only)	All	All	All	All
Half-Duplex	Yes	Yes	With pilot channel	Yes
Multi-Satellite	Yes	No	Yes (#1)	Yes (#1)
Complexity of Hardware and Interfaces (1-10)	7	5	6	7
Unit Cost - 10,000's	499.	454.	454.	464.
100,000's	436.	391.	391.	401.
Installation (1-10)	6	8	5	8
User Interfaces	No	Yes	No	No

(Note #1: Possible isolation problems due to accuracy limits)

2.0 STUDY OBJECTIVE

The objective of this study is to perform detail design studies, cost analysis and laboratory tests on selected antenna and antenna pointing concepts. The antenna gain requirement is 10 dBic minimum. The required antenna isolation for two satellite located at 105° W and 135°W is 25 dB minimum. The studies are to include the following.

2.1 2X5 Mechanically Steered Array. The linear array is to be studied for this application. A partial or complete array is to be constructed to determine antenna performance. Several techniques for reducing radiation at the horizon and below are to be studied including surface corregation, impedance surfaces and edge modifications. Provide updated isolation data for the multisatellite systems. Identify major cost drivers and total cost in fabricating this antenna in quantities of 10,000 and 100,000 units.

2.2 1X16 Ring Array. Construct a partial ring array and determine the operating characteristics of the full ring array. Study phase shifting techniques, determine antenna performance, and provide updated isolation for the multiple satellite case. Identify cost drivers and determine the unit cost for 10,000 and 100,000 units. This portion of the study was cancelled under JPL's instruction.

2.3 Mechanically Steered Low Profile Conformal Array. Investigate the performance characteristics of the low profile conformal array. Determine major cost drivers and total cost in fabricating this antenna in quantities of 10,000 and 100,000. Provide multiple satellite isolation data.

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2.4 Pointing Systems. Identify various low cost and accurate pointing concepts and techniques for pointing the antenna main beam for the following satellite scenarios:

- Single geostationary satellite at -105°W
- Two geostationary satellites at -135 and -105°W with both satellites in a common frequency band but opposite polarization sense. Each vehicle is to communicate with one satellite while discriminating against the other.
- Three satellites located at -75°, -105°, and -135°W with the center satellite operating with opposite polarization sense to the other satellites.

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3.0 2X5 MECHANICALLY STEERED LINEAR ARRAY

3.1 Array Construction and Test. The array elements studied for potential use in the 2x5 array were a modified cavity backed crossed slot and the square microstrip patch as shown in Figure 3.1-1 and 3.1-2. The first element to be evaluated was a heavily dielectrically loaded 4-inch square crossed slot. The element patterns shown in Figure 3.1-3 are broad, having approximately 120 degrees - 3dB beamwidth and have good circularity. The first attempt to array these crossed slots showed the elements broad beamwidth to be an undesirable trait. The low gain achieved with such a broad beam indicated a need for at least eight elements. Two methods for arraying the eight elements were investigated - staggering one antenna behind the other and stacking one above the other. Staggering has the advantage of being low profile while stacking the elements is desirable because there is no blockage problem. The attempts made at staggering the elements were not successful due to blockage problems. Stacking these broad beam elements was fairly successful and elevation patterns were recorded in Figure 3.1-4 indicating that eight elements arrayed in this manner could supply the required gain (10 dBic). The use of a patch antenna was investigated with the intent of decreasing the cost of the antenna by having fewer more-directive elements. Figure 3.1-5 shows the patch's half power beamwidth is approximately 60 degrees. The first results indicated, that due to its increased directivity, one patch had nearly the same pattern characteristics as a pair of stacked four crossed slots. A 1x4 element array of patch antennas spaced eight inches apart was constructed as shown in Figure 3.1-6. The array had sufficient gain and a broad enough elevation plane beamwidth to supply the required elevation coverage from 20 to 60 degrees without elevation steering. The cost advantages of this type array over the eight element cross slot array led to focusing all further study objectives on this four element array.

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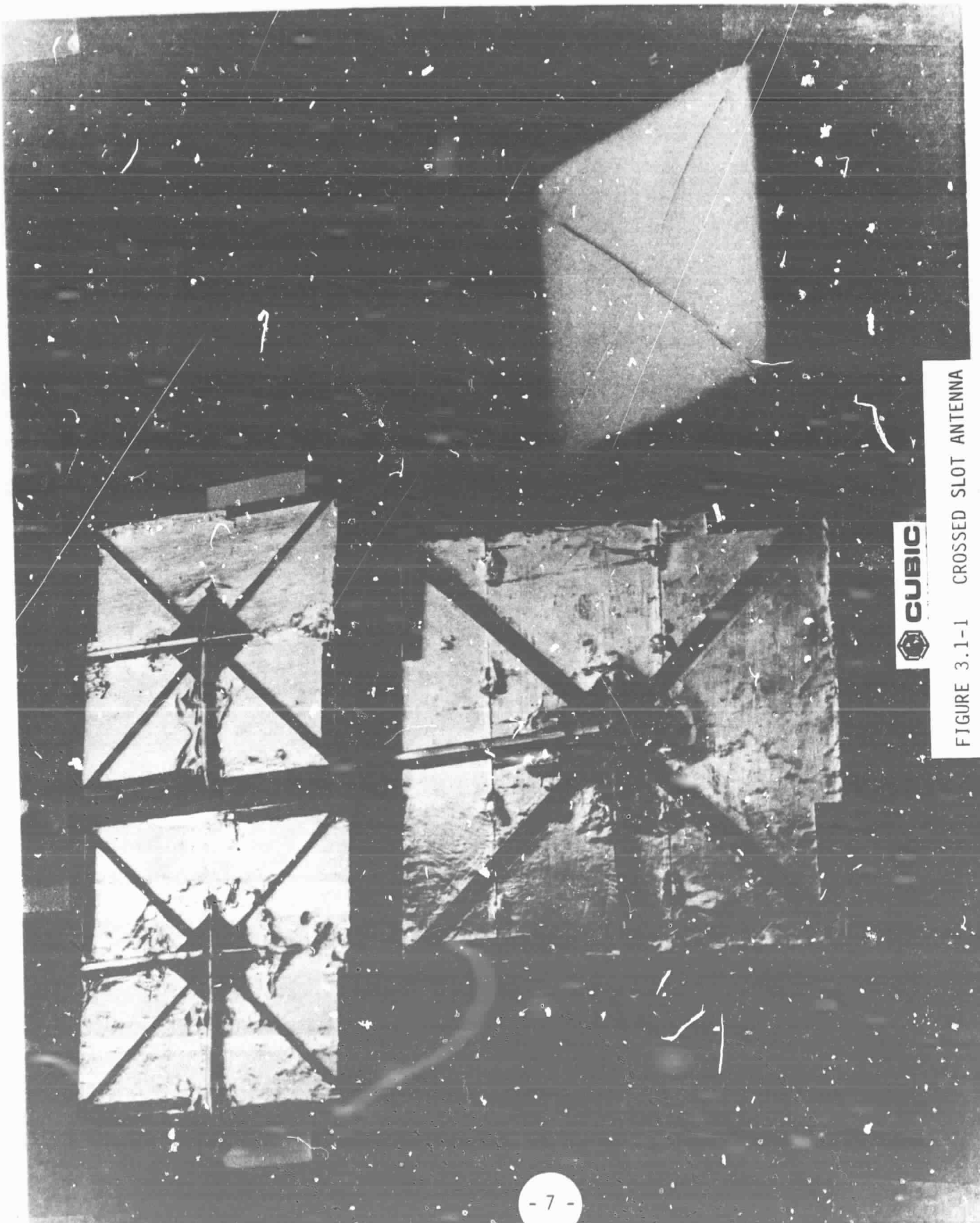

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FIGURE 3.1-1 CROSSED SLOT ANTENNA

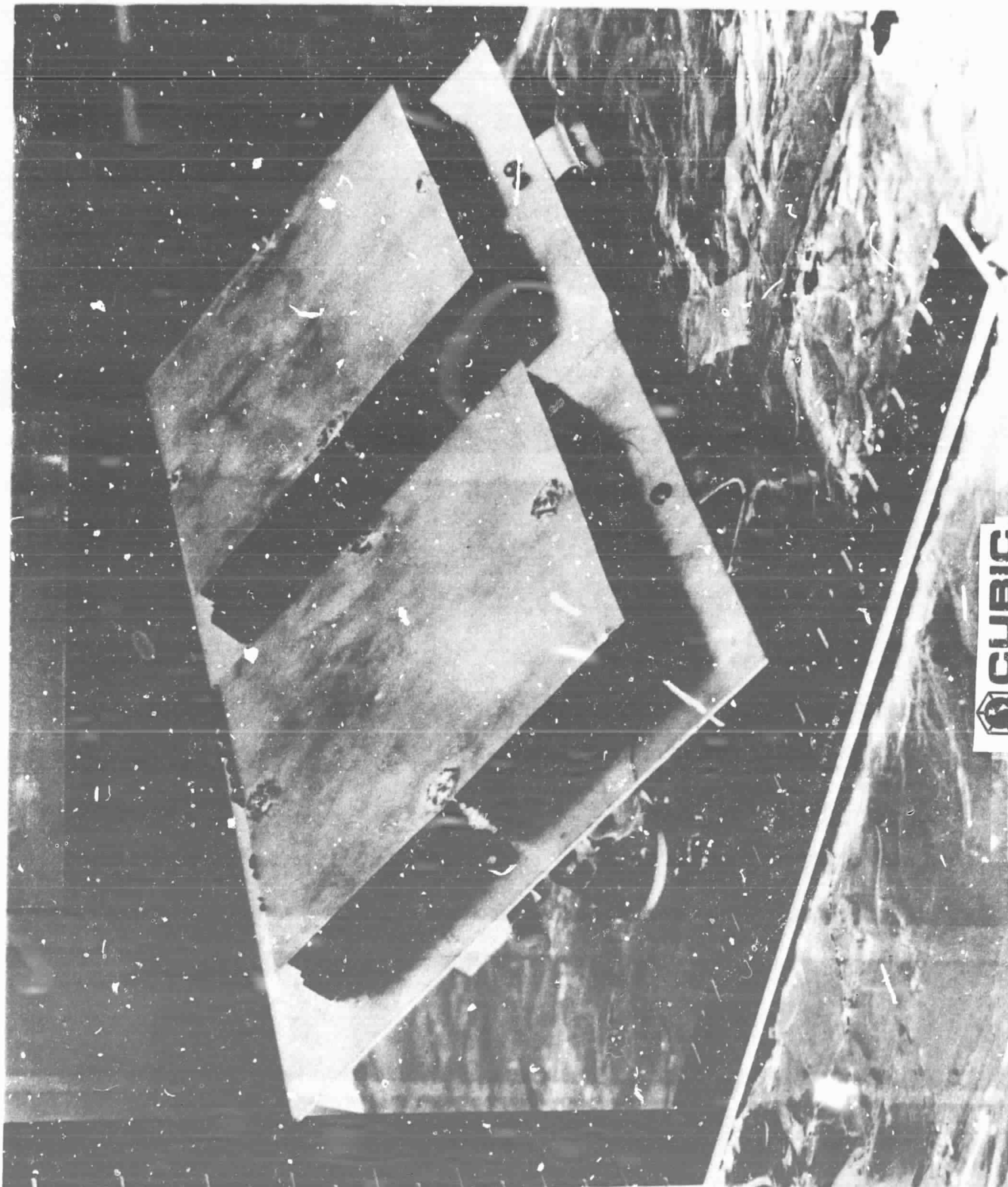

FIGURE 3.1-2 TWO SQUARE PATCH ANTENNAS

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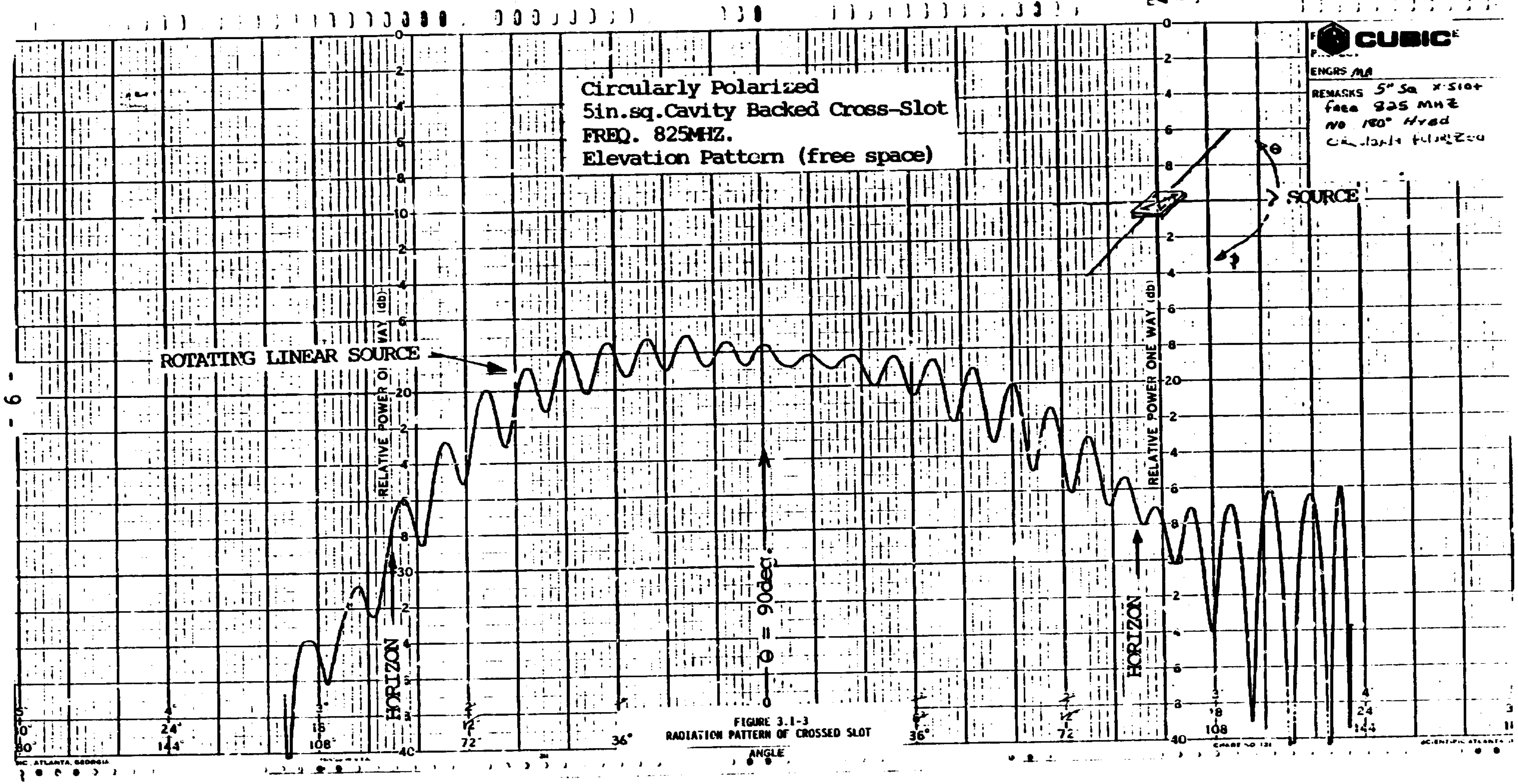

FIGURE 3.1-3
RADIATION PATTERN OF CROSSED SLOT

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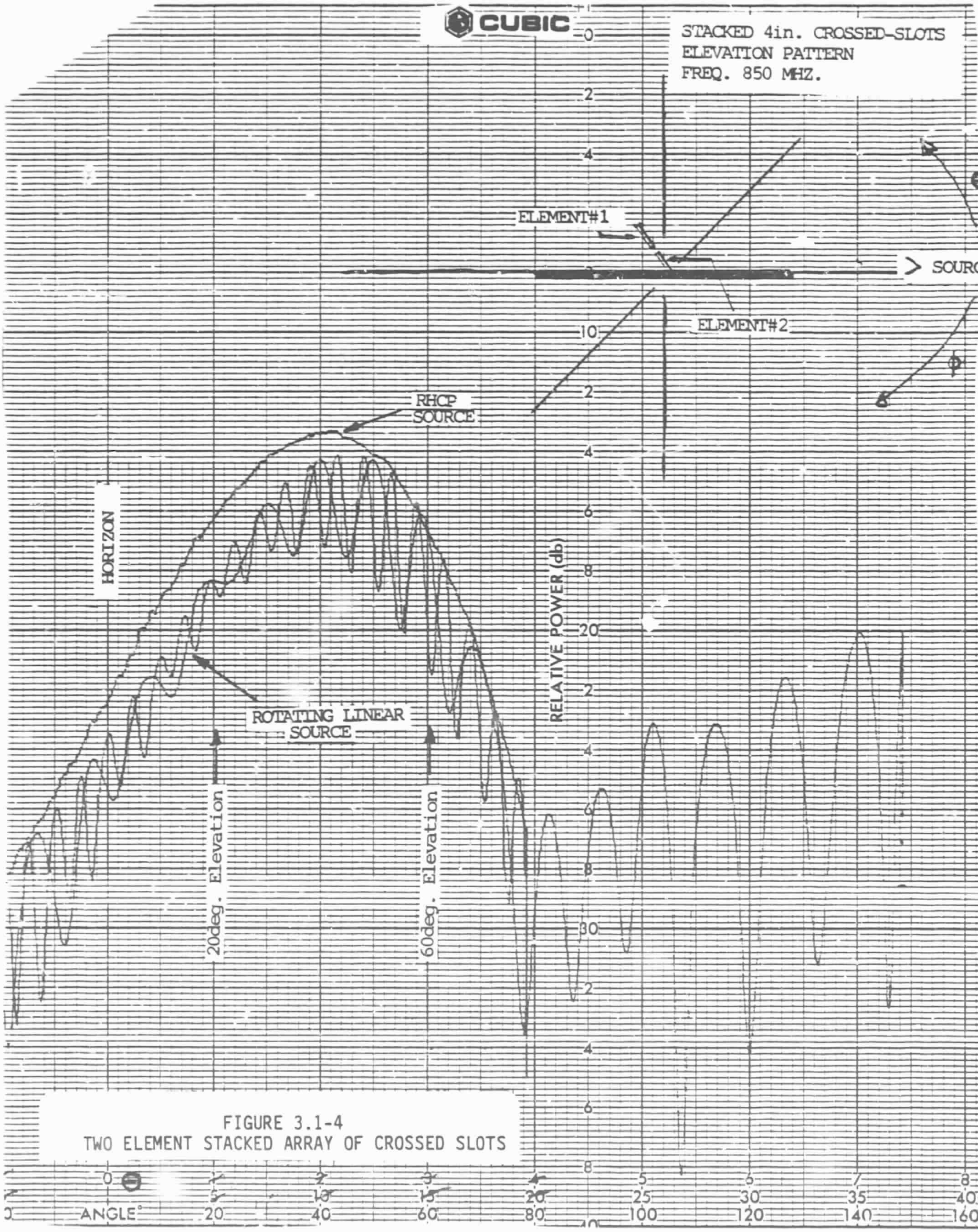

FIGURE 3.1-4
TWO ELEMENT STACKED ARRAY OF CROSSED SLOTS

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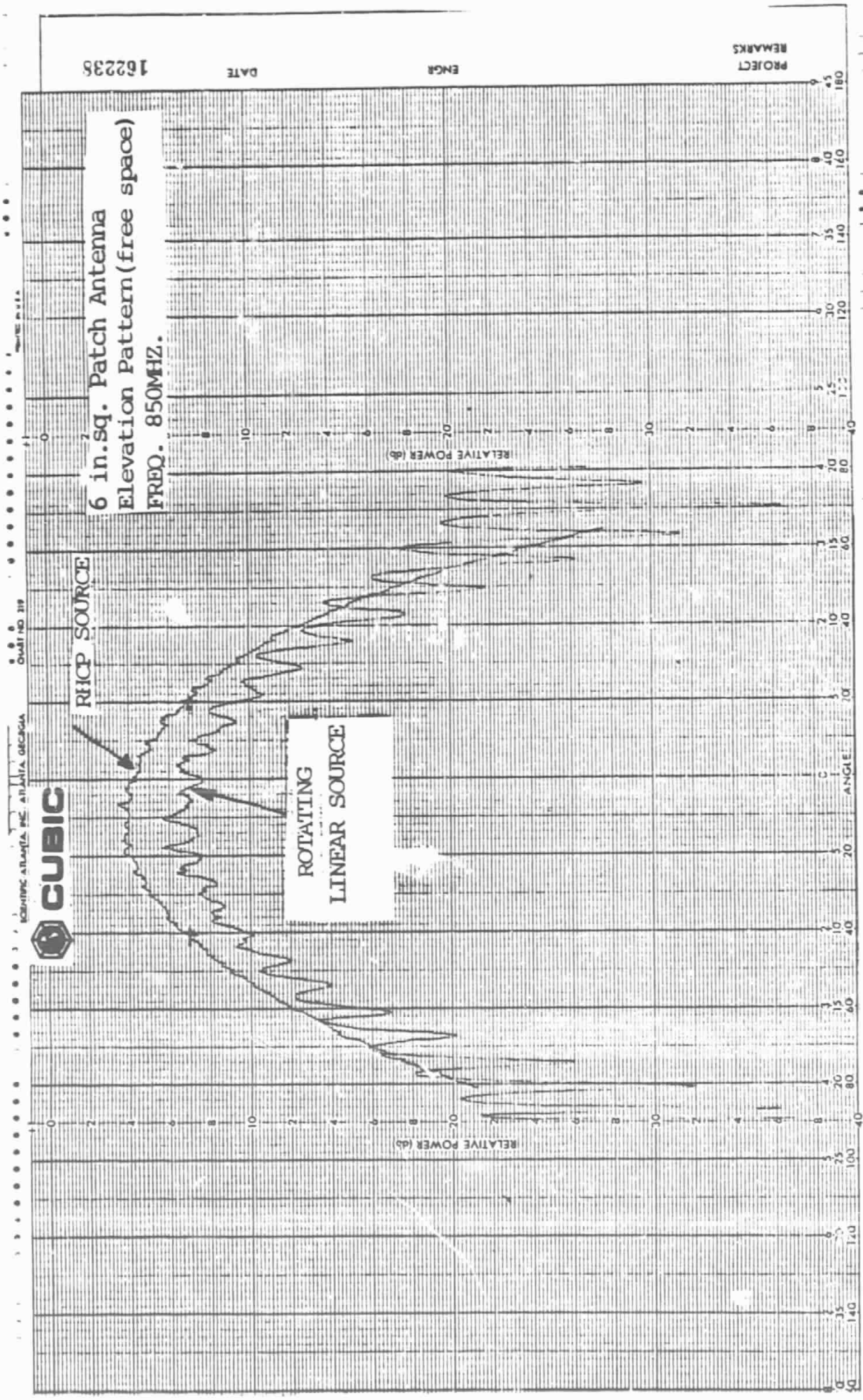

FIGURE 3.1-5
RADIATION PATTERN OF MICROSTRIP PATCH

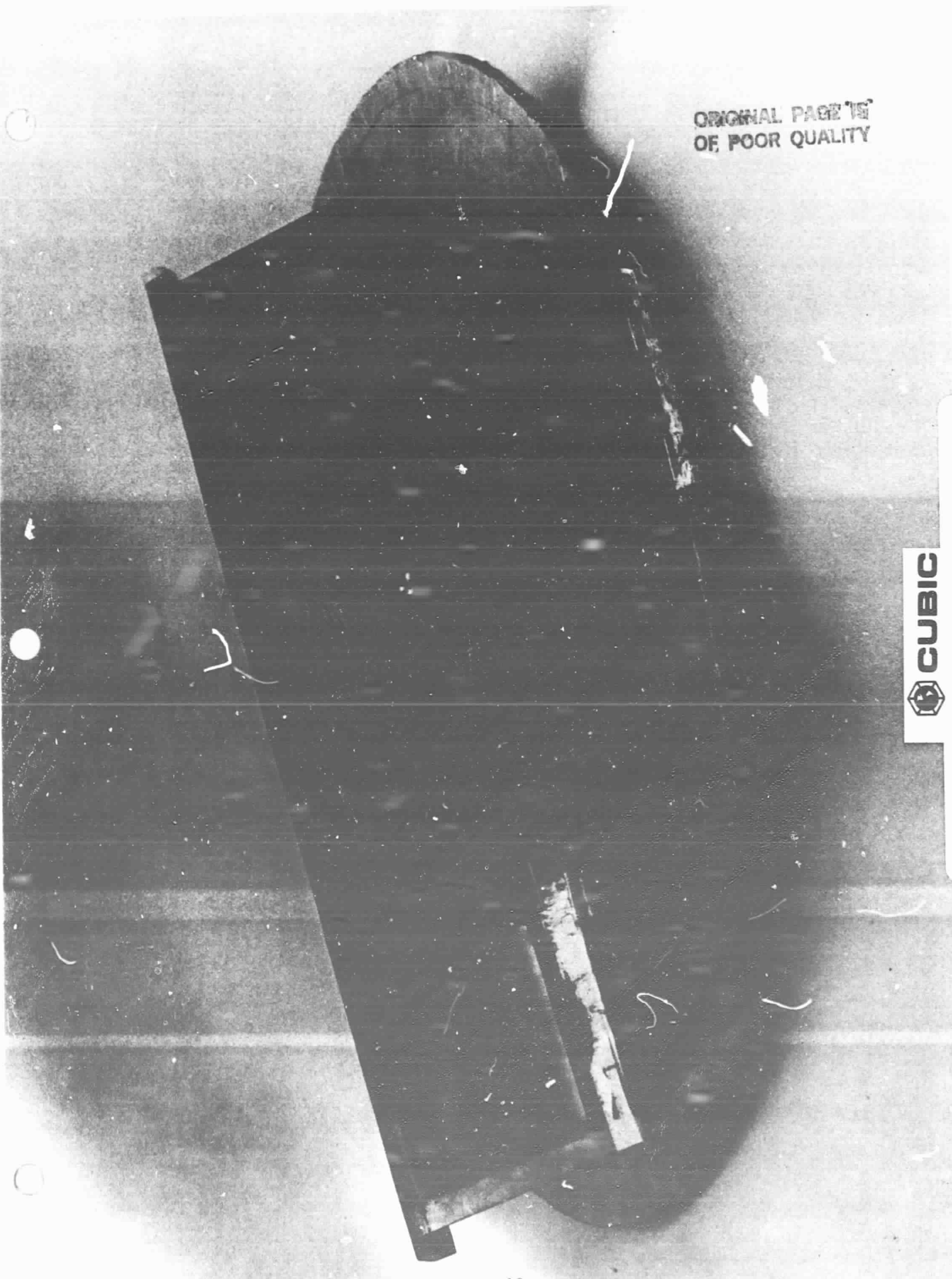

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FIGURE 3.1-6
1X4 ARRAY WITH CONTROL OF PATTERN FALL-OFF

3.2 Surface Corrugation Study. The surface corrugation study initially focused on construction of a corrugated ground plane that would cause a reduction in the vertically polarized component of the antenna's circularly polarized field. The corrugation caused a decrease in the "on the horizon" pattern coverage but did so with too great a reduction in the coverage at 20 degrees. The lack of a sufficiently steep slope to the fall off caused by the corrugation raised doubts about its potential use for this application. The antenna (1x4 array) has an axial ratio of approximately 3dB "on the horizon" which indicates that a successful technique for achieving the fall off would need to cancel both the vertically and horizontally polarized fields. A technique for achieving this fall off was developed. This technique takes a portion of the radiation from the antenna and passes it through a dual polarized phase shifter to cancel some of the radiation on the horizon. The dual polarized phase shifter is a ridge-loaded waveguide whose shape and length is tailored to provide the desired cancellation. This technique was successfully tested using the 1x4 element array shown in Figure 3.1-5. The radiation pattern in Figure 3.2-1 shows that the drop off can be improved by up to 10 dB using this technique. Figure 3.2-2 shows the effect of the waveguide with respect to axial ratio.

3.3 Satellite Isolation. Contour plots were made of the 1x4 array radiation patterns using co- and crossed polarization. Satellite pointing angles for various geographic extremities of CONUS were computed in Table 3.3-1 and included on the contour plots to illustrate the range of isolation between satellites which is achievable. The three satellite case presents potential isolation problems with both co-polarized and cross-polarized interference signals. Therefore, an accurate assessment of the isolation situation requires analysis of both co- and cross-polarized contour plots. Figure 3.3-1

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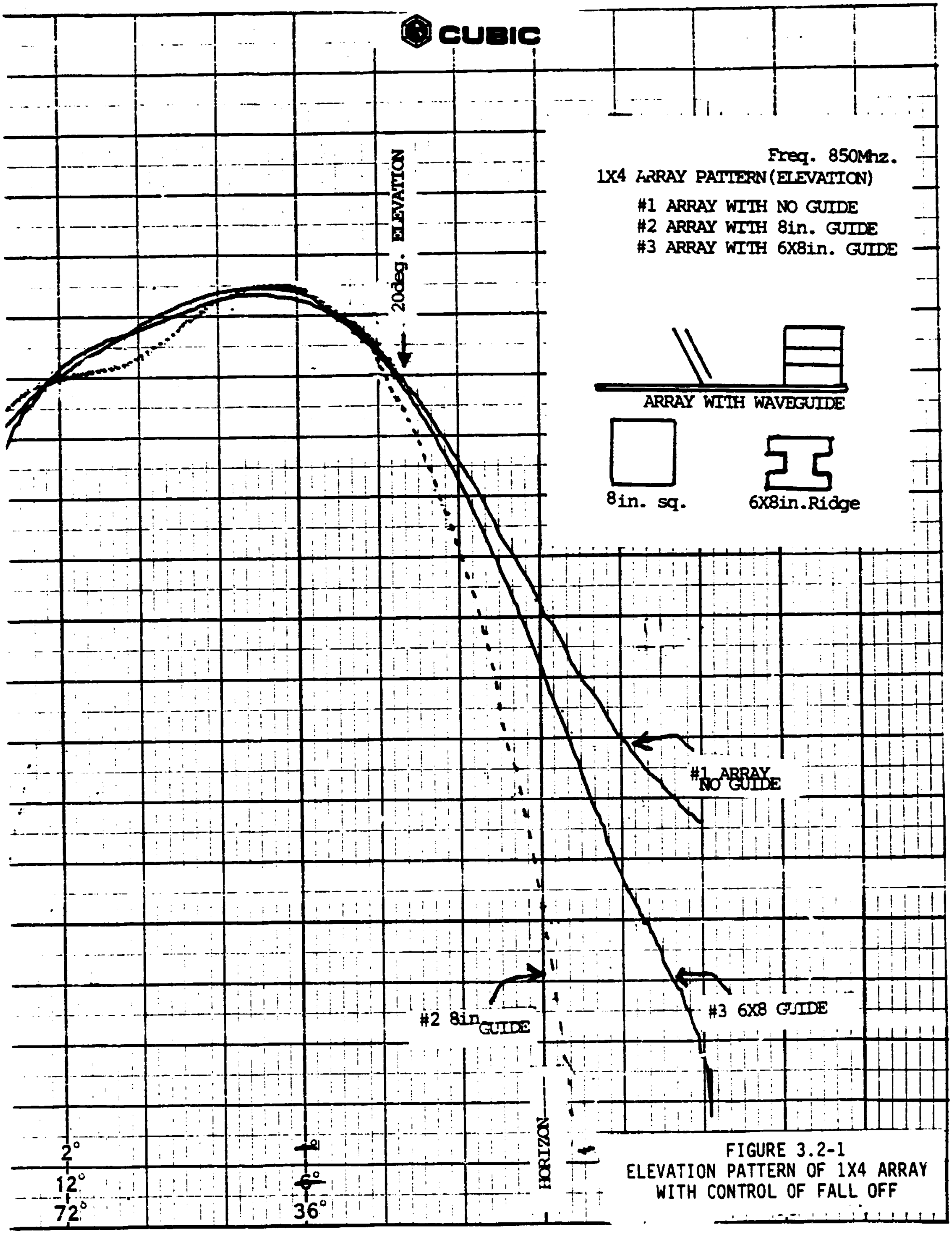

FIGURE 3.2-1
ELEVATION PATTERN OF 1X4 ARRAY
WITH CONTROL OF FALL OFF

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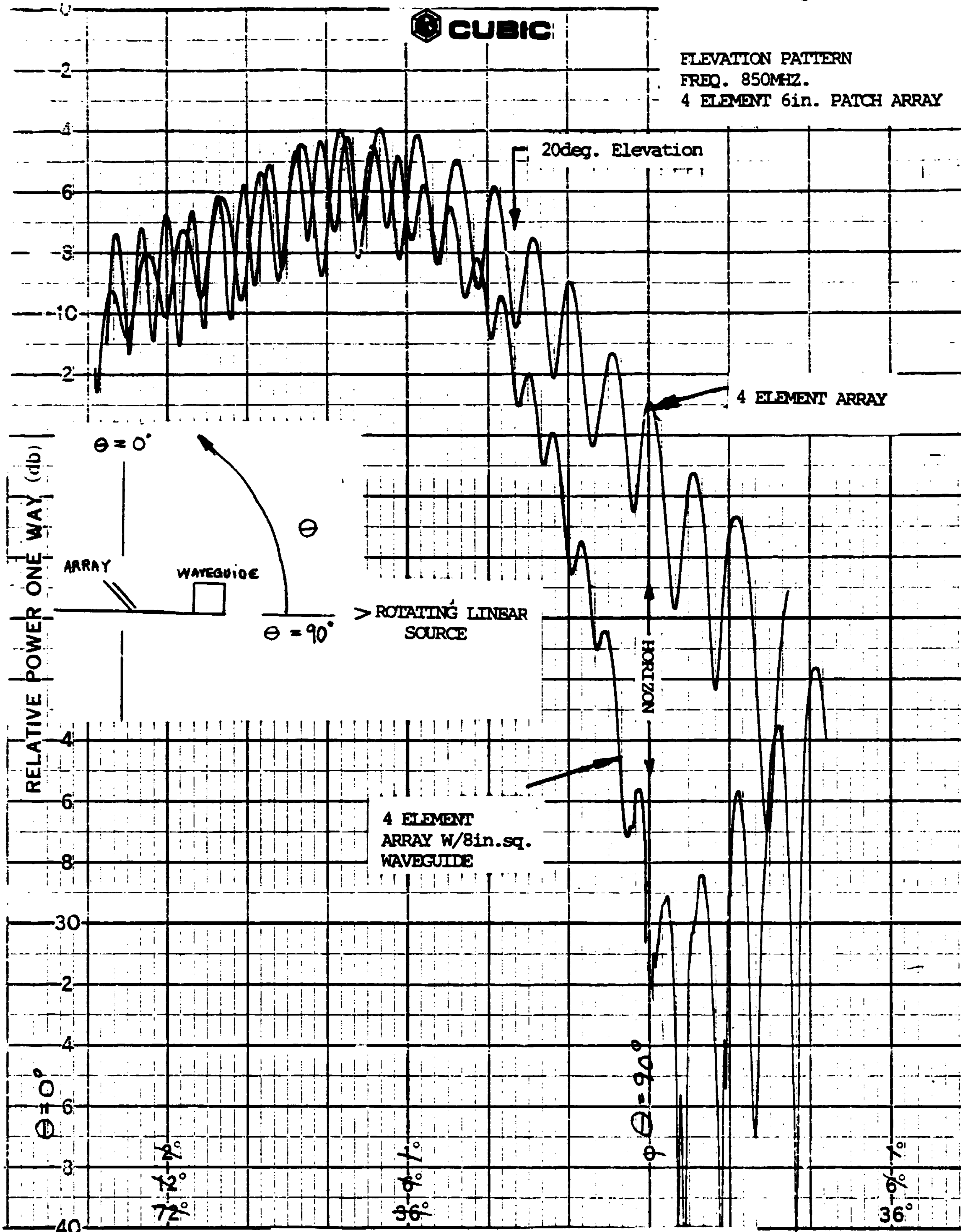
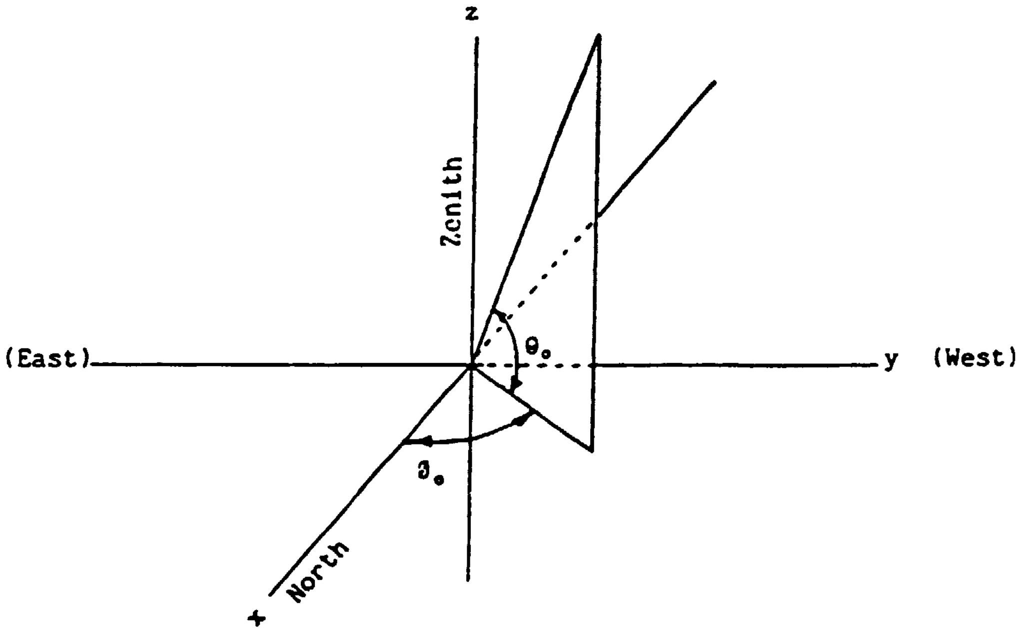


FIGURE 3.2-2
ELEVATION PATTERN WITH AND WITHOUT WAVEGUIDE

TABLE 3.3-1

	LAT θ_e	LONG ϕ_e	$\phi_s = -75°$ SATELLITE #1 75° W Long θ_o	ϕ_o	$\phi_s = -105°$ SATELLITE #2 105° W Long θ_o	ϕ_o	$\phi_s = -135°$ SATELLITE #3 135° W Long θ_o	ϕ_o
Key West FL	25°	-82°	60°	-163°	51°	+135°	25°	+108°
East Port ME	45°	-67°	38°	+169°	26°	+132°	7°	+106°
Penasse MN	49.5°	-95°	30°	-154°	32°	+167°	22°	+132°
Cape Flatters WA	49°	-125°	17°	-122°	31°	-154°	33°	+167°
Imperial Beach CA	32.5°	-117°	31°	-121°	50°	-158°	47°	+149°
Brownsville TX	25.5°	-97.5°	51°	-136°	59°	+163°	39°	+119°



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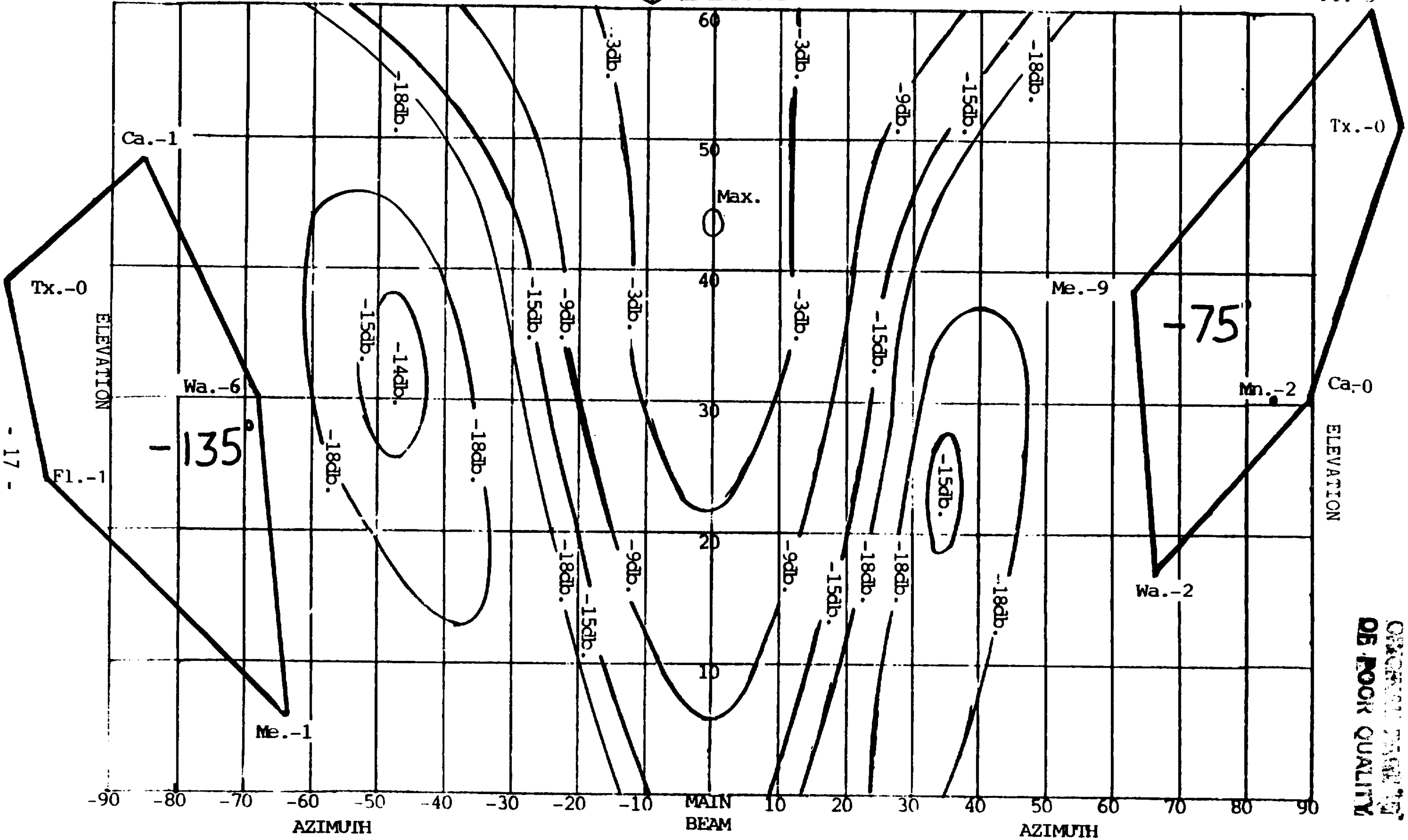

CO-POLARIZED PATTERN

FIGURE 3.3-1

THREE SATELLITE CASE CO-POLARIZED

is a co-polarized countour plot; the trapazoidal regions shown represent relative pointing angles to the non-desirable co-polarized satellite. The relative pointing angles were computed assuming the mobile antenna to be well pointed in the direction of the primary satellite. The figure shows that when the mobile antenna's main beam is pointed toward the 135° W. longitude satellite the pointing angle to the 75° W. longitude satellite (represented by the area marked -75) is such that the antenna's gain (with respect to peak) is down by more than 18 dB. Figure 3.3-2 is a cross-polarized contour plot that shows isolation between satellites of different polarizations. The two areas marked -75 and -135 are applicable when the mobile antenna main beam is pointed at the 105°W. longitude satellite, and the areas marked -105 represent relative pointing angles to the 105° W. longitude satellite when the mobile antenna is tracking the -75° or -135° satellite.

The data presented shows the percentage of CONUS that will experience a given magnitude of Isolation. It was believed that amplitude tapering of the array would generally improve the isolation by reducing sidelobes. However, because of the small angular separation in the three satellite case isolation suffers due to broadening of the main beam associated with tapering. Figures 3.3-3 and 3.3-4 show the two satellite cases for -80°/-113° and -105°/-135° satellite locations. In this case tapering the amplitude distribution will increase isolation. Again trapezoidal areas represent the look angle to the secondary satellite when the main beam of the mobile antenna is pointed at the primary satellite. These look angles were calculated for the CONUS Geographic extremes and marked accordingly. The lines on the plots represent gain with respect to peak gain of the array, which occurs at approximately 45° in elevation.

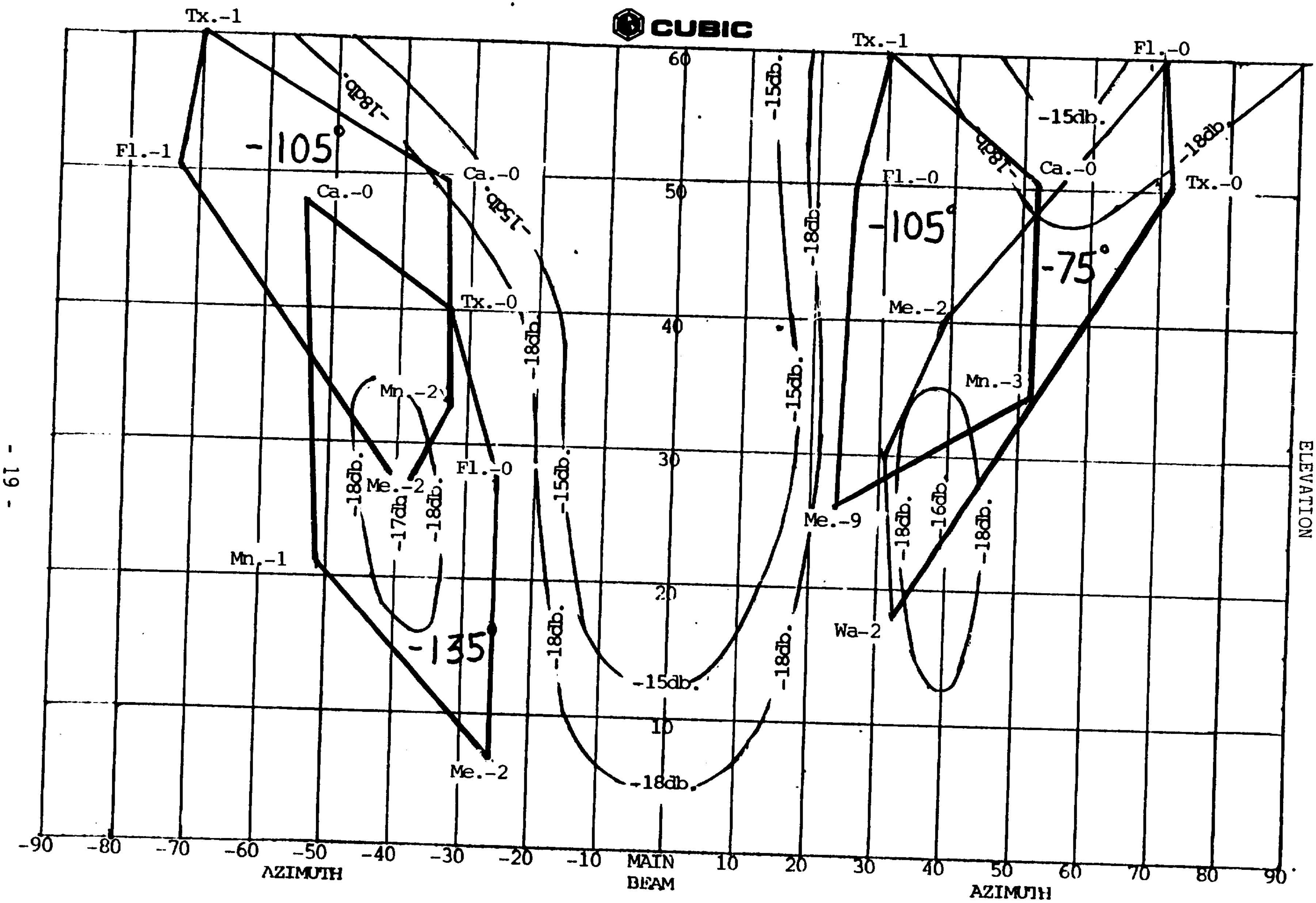

FIGURE 3.3-2
THREE SATELLITE CASE CROSS POLARIZED

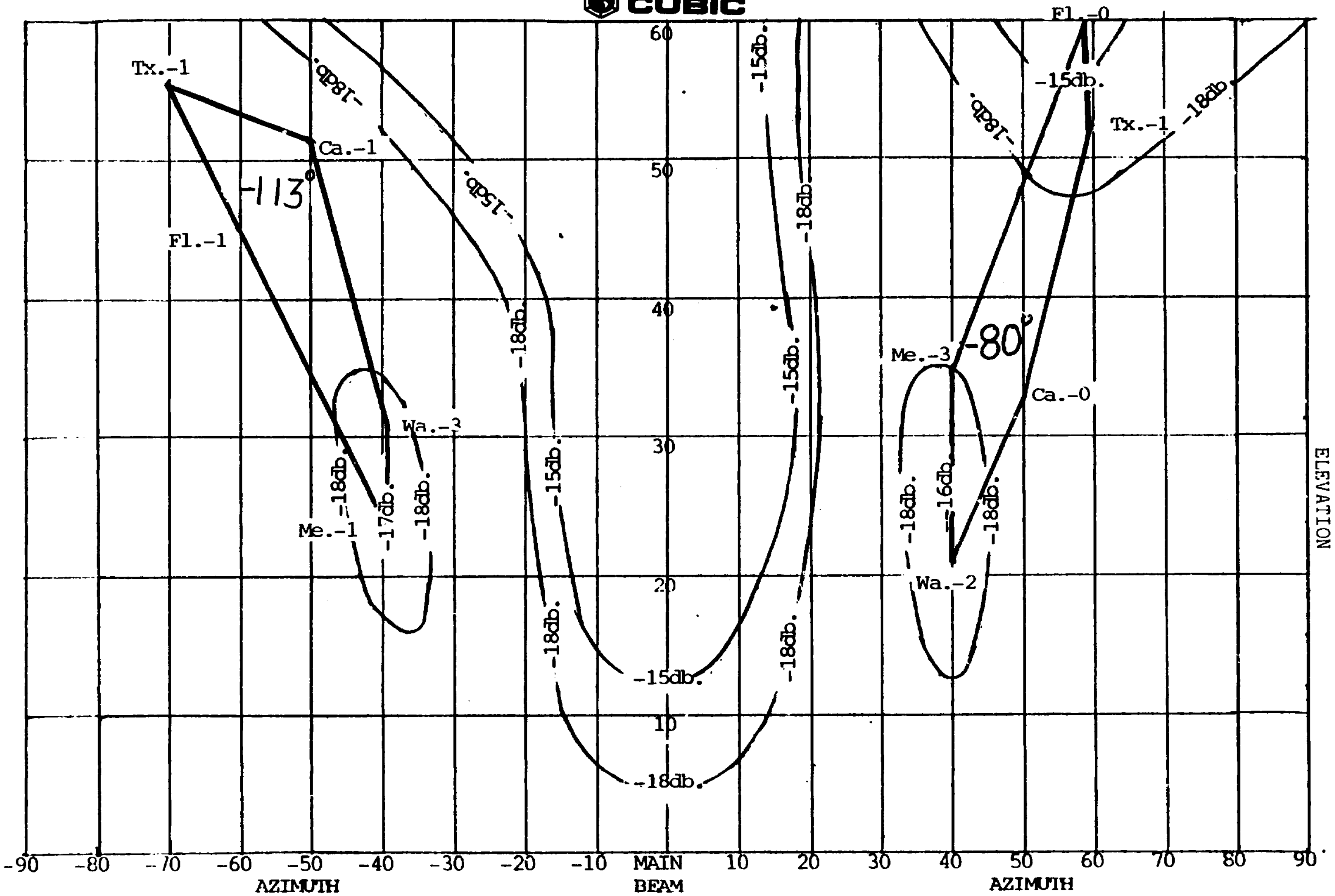

FIGURE 3.3-3
TWO SATELLITE CASE CROSS POLARIZED

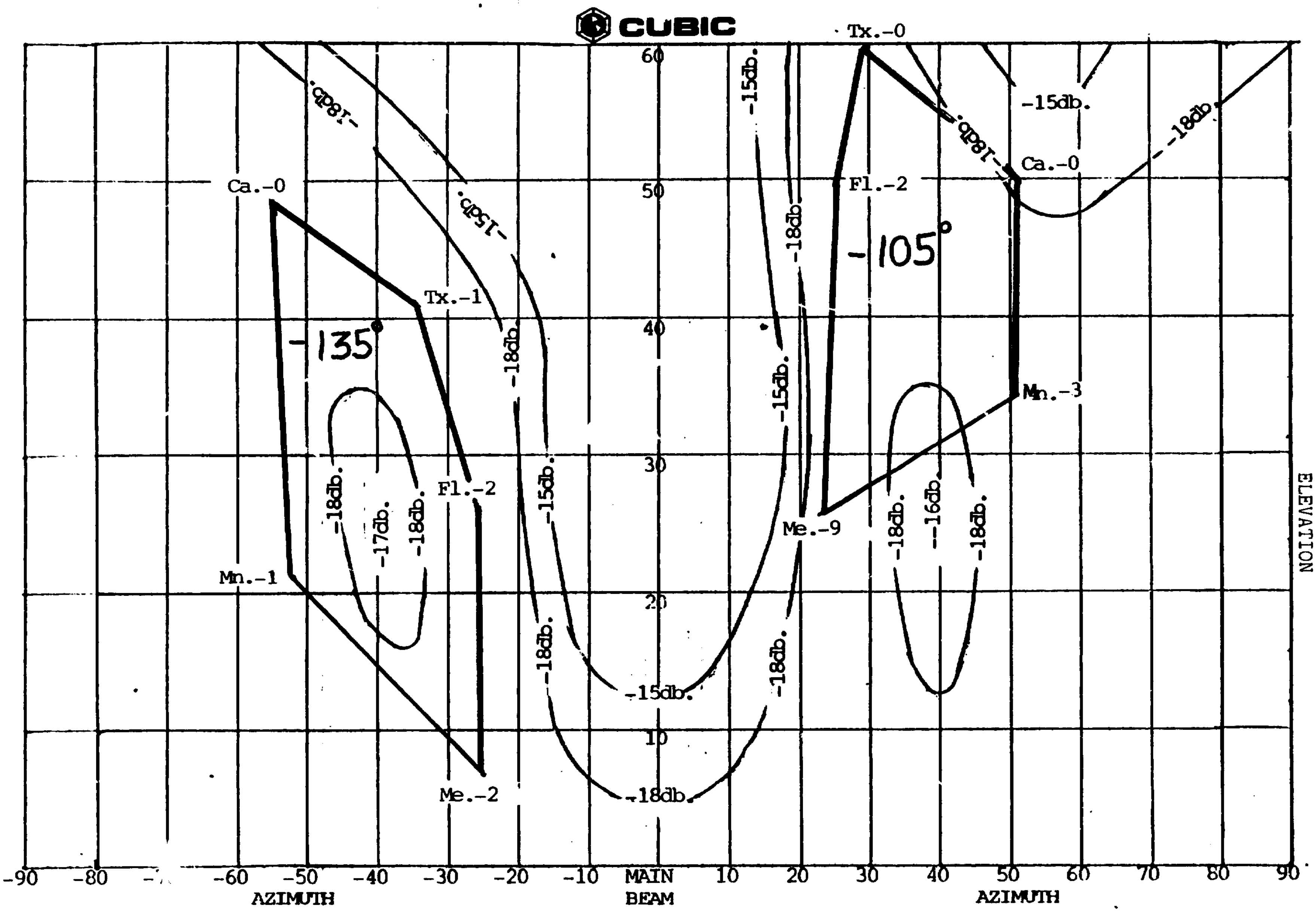

FIGURE 3.3-4

TWO SATELLITE CASE CROSS POLARIZED

Differences in elevation look angle for different CONUS locations must be adjusted for loss in gain due to elevation gain dropoff, because "gain with respect to peak" isolation numbers assume all signals are received on the peak of the main beam (at 45° elevation). The plots can be compensated for this effect by subtracting the number listed with the CONUS location from the "with respect to peak gain" number read from the plot. For example, on Figure 3.3-3, when the main beam of the mobile antenna is pointed at the -113° satellite the isolation in Maine from the -80° satellite is -18 - (-3) = -15 dB. Because the elevation look angle to the 113° satellite in Main is approximately 25° or 3 dB below the peak gain (45°). The two satellite case was studied for optimum satellite location. This -85°/-110° satellite scenario is shown in Figure 3.3-5. It provides 18 dB isolation over the majority of CONUS and may be improved with amplitude tapering to perhaps 20 dB.

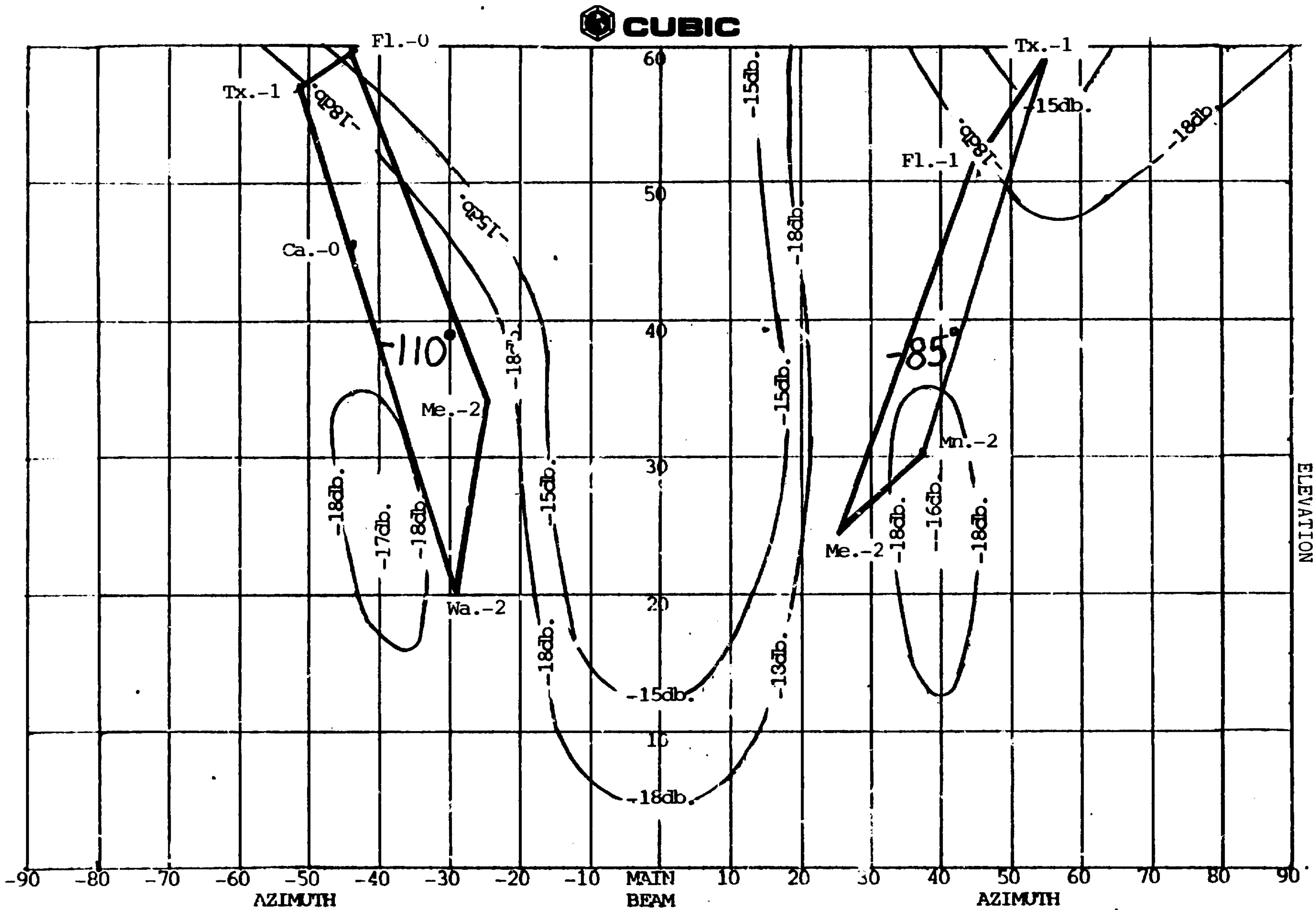

FIGURE 3.3-5
OPTIMUM TWO SATELLITE POSITION

4.0 MECHANICALLY STEERED CONFORMAL ARRAY

The earlier report described a fully electronic steerable conformal ($\leq$3 inches height) array. This array had phase shifters at each element and as a result was very expensive. An alternative to that design is to make a conformal array and mechanically steer the beam by rotating the antenna. The elevation pattern is shaped by the basic element pattern and fixed phase feeding of the antenna through a stripline network to produce a beam maximum at about 40 degrees. The radiating structure is sketched in Figure 4.0-1. The peak gain will be 13 dB, while the gain at 20 and 60 degrees elevation angles will be 9 dB. Preliminary pattern work shows that by tilting the array elements an axial ratio of 4 dB may be achievable at 20 degrees above the horizon. Figure 4.0-2 shows an elevation pattern for one element on a three-foot circular ground plane. The circular aperture will result in lower sidelobe levels. The result will be satellite isolations of 18 dB.

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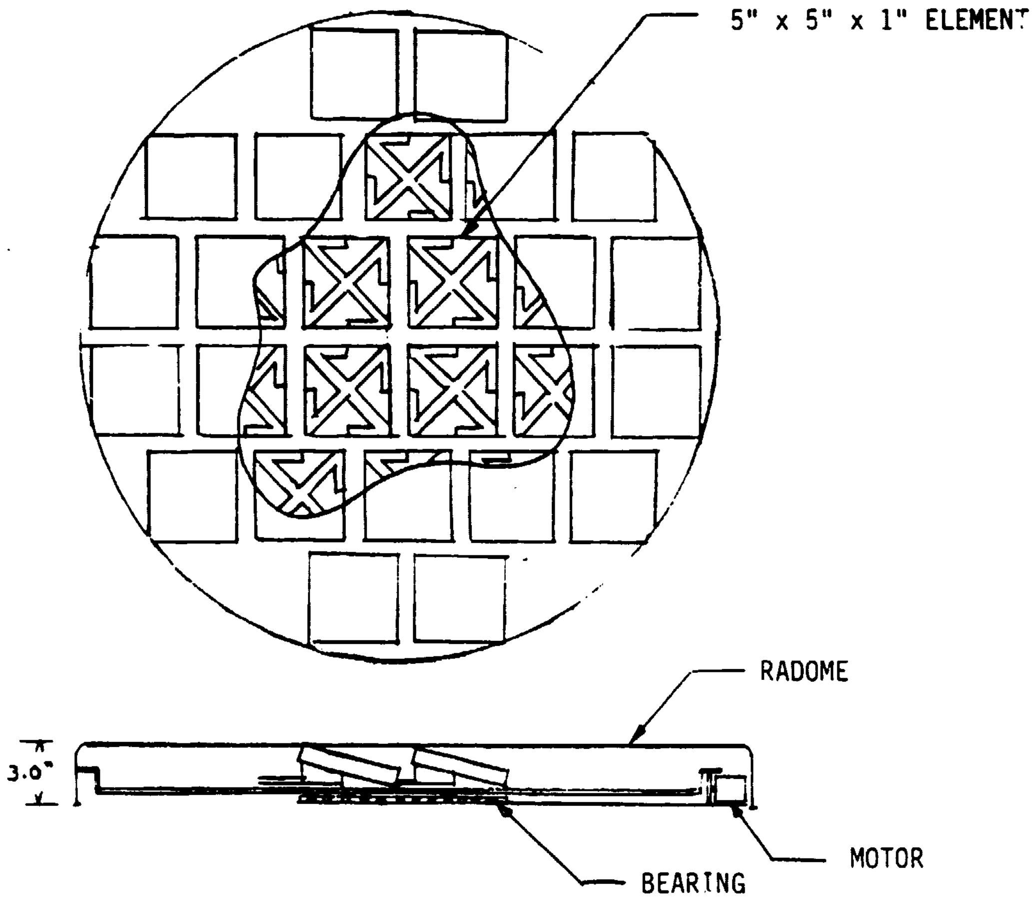

FIGURE 4.0-1. CONFORMAL ARRAY

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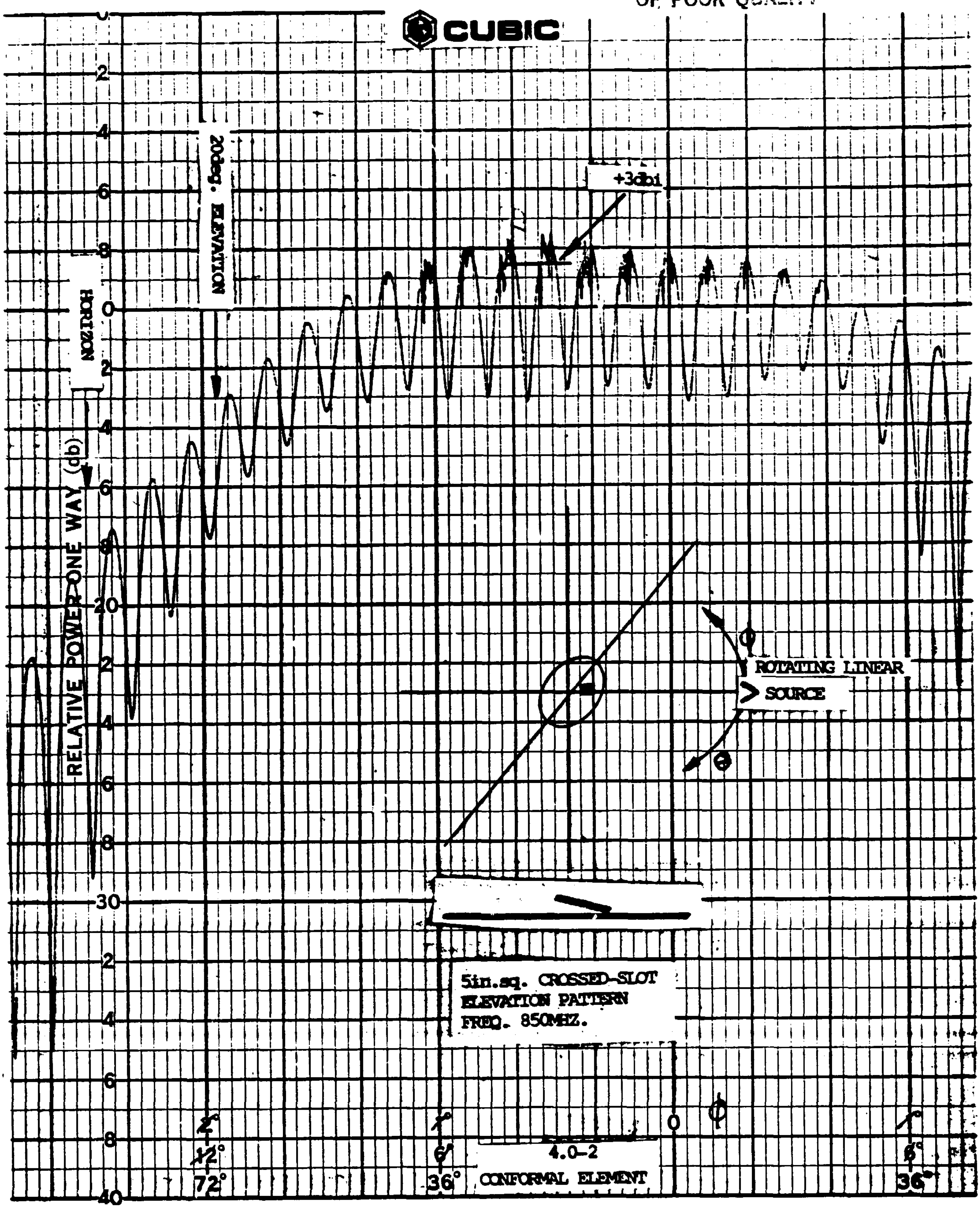


5.0 ANTENNA BEAM POINTING

Several methods of acquiring and tracking the satellite were studied. Each system is described in detail and the advantages and disadvantages of each system outlined. Price models were made in cases where the system is practical. The antenna pointing techniques presented in the report are:

- The open loop magnetic compass
- The AGC method.
- The closed loop pseudo monopulse
  - Unaided
  - Compass aided
  - Rate gyro aided
  - Using a separate receiver.

5.1 Open Loop Magnetic Compass. A block diagram of the open loop magnetic compass is shown in Figure 5.1-1. In the figure, the compass is mounted on the car. Compass output is a voltage proportional to the angle of the antenna car heading relative to indicated magnetic north. The desired satellite position is chosen from a control indicator located on the front panel of the transceiver. The difference between the output of compass voltage and the satellite position potentiometer voltage is an error voltage which is amplified and used to turn the antenna to the desired position. When the desired position is reached, the error voltage goes to zero and the antenna stops. The satellite position knob is then adjusted to peak the receiver's AGC voltage by visually observing the AGC voltage read out on the front panel of the transceiver. The advantages and disadvantages are summarized in the following.

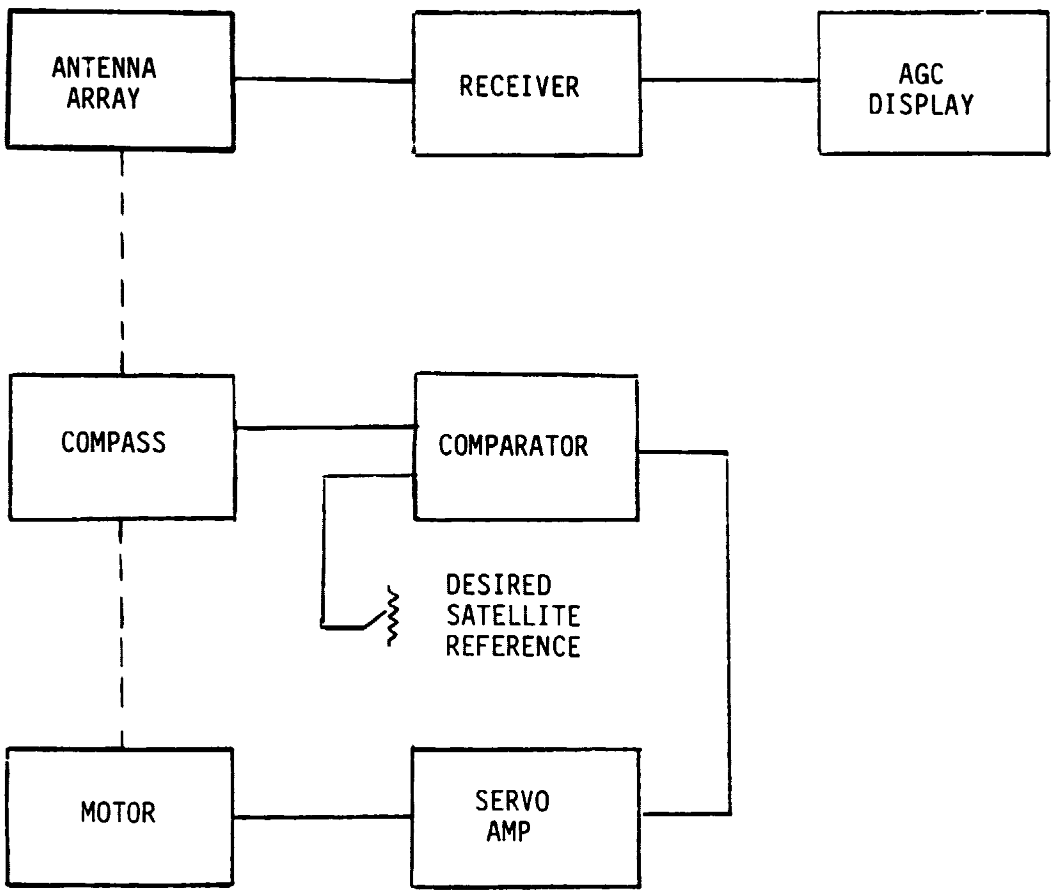


FIGURE 5.1-1

OPEN LOOP MAGNETIC COMPASS ANTENNA POINTING

5.1.1 Advantages.

- o Requires no signal acquisition or tracking
  - o Independent of fading
  - o Independent of signal level
  - o Adequate accuracy when compensated
  - o Rapid alignment after turn on.
  - o No problem with satellite selection
- o Mature technology.

5.1.2 Disadvantages.

- o Error can result from vehicle acceleration (starting, stopping, turning, or due to rough roads).
- o Requires compensation of declination ($\pm$ 20 degrees across CONUS). Compensation is a function of longitude and latitude.
- o Requires compensation for installation. Local magnetic fields can introduce error. Installation may require "compass turning" for each installation.
- o Compass may require gimbal mounting to prevent error due to tilt resulting from uphill/downhill travel.
- o Compass and electronics may require shielding from transmitter and/or power supply magnetic effects.
- o A few locations have anomalies which produce large errors.
- o May require compensation of northerly turning error due to vertical component of earth's magnetic field (Compensation a function of latitude).
- o Lack of pointing accuracy will reduce isolation.

5.1.3 Compass Accuracy. The concern over the compass accuracy led to a detailed study. The areas that ~e investigated were as follows:

1. Transient Road Errors: Road testing at various speeds and directions: noting the errors induced when passing under an overpass or bridge; noting the errors when passing close by large trucks, railroad trains and heavy traffic; and noting the effects when transversing long steel bridges and passing directly over railroad tracks.

2. Dynamic Errors: Errors created in stopping, starting and acceleration, response around curves and rough roads.

3. Vehicular Induced errors: Required compensation due to vehicular induced errors, differences with various vehicles, and placement of the compass unit on the vehicles.

A compass used to control the position of a shaft was used for this investigation. The compass is contained in the course setter.

The Test Equipment used is outlined in the Figure 5.1.3-1. A photograph of the equipment installed in a car is shown in Figure 5.1.3-2.

5.1.3.1 Transient Road Errors. Dynamic transient road errors were recorded at various highway speeds, conditions and directions. Errors observed as the result of heavy traffic were concluded to be nill. Errors observed passing in the close proximity of large trucks were concluded to be nill. A loaded passing railroad train in close proximity to the test vehicle had little or no effect on the compass sensor. An exception occurred by a large trailer containing a large piece of earth moving equipment causing an offset of the compass by approximately 10 degrees. Little or no deviations were observed when

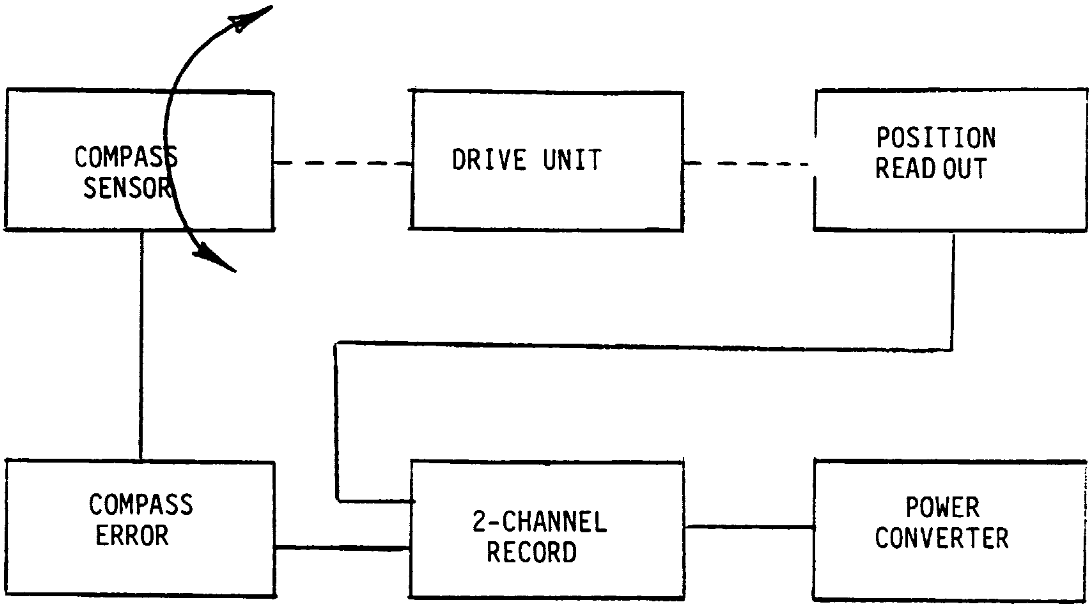


FIGURE 5.1.3-1

COMPASS EVALUATION EQUIPMENT

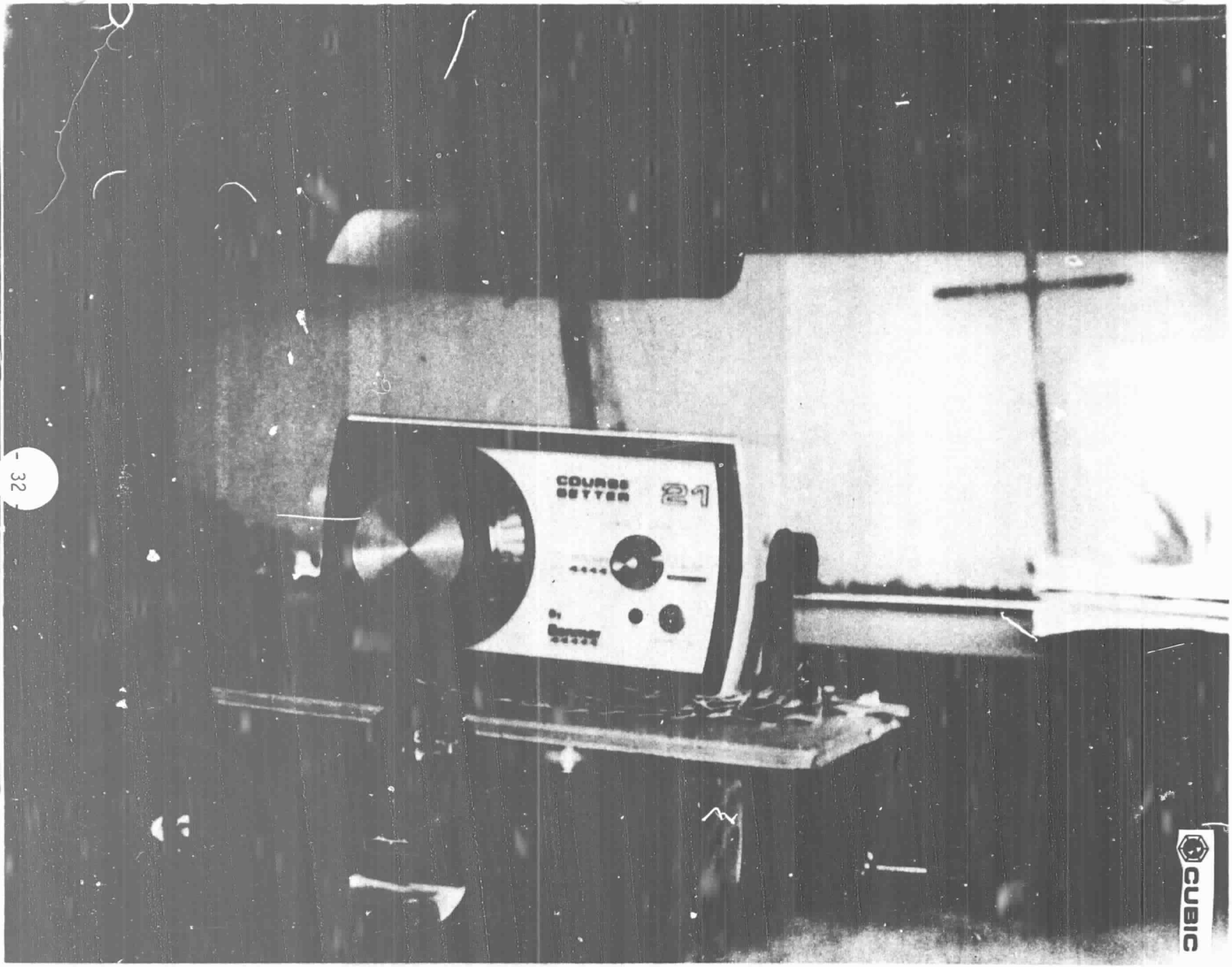


FIGURE 5.1.3-2 COMPASS EQUIPMENT

passing under a bridge or overpass at normal highway speeds. A 5-8 degree deviation was observed when passing over a bridge or overpass. An exception occurred on a long steel bridge, such as the San Diego Coronado Bay Bridge, which caused the compass to wander 20-30 degrees while transversing the bridge. When crossing over a railroad overpass, the compass would momentarily deviate 30-40 degrees.

5.1.3.2 Dynamic Errors. Starting and stopping the vehicle engine created problems when the sensor was in the close proximity to the engine. After starting the engine, and at engine idle, the compass would offset or deviate approximately 10-20 degrees. Once the vehicle was traveling at normal highway speeds, this error would disappear.

A compass unit was gimbled for a $\pm$15 degree inclination and operated satisfactorily under these conditions. Compass sensor would follow slew rates up to 30 degrees per second per second. Normal stopping and starting had little or no effect.

The final conclusion was that under normal highway conditions, the compass tracked approximately 95 percent of the time.

5.1.3.3 Vehicular Induced Errors. An aircraft compass rose, located at Montgomery Field airport was used as a reference for determining vehicle mounted compass alignment. Typical vehicle induced errors are shown in Figure 5.1.3-1. Vehicular induced errors can be reduced by magnetic compensation. The compass sensor must be equipped with magnetic compensators; the set of compensators is for the north/south alignment, the other set of compensators is for the east/west alignment. The vehicle would be required to head north, adjusting the compensators and subsequently east, south, and west - and

finally, points in between. Testing indicated that different vehicle models were not alike.

The cost and methods for alignment would reflect in the Customer's installation charges. The time required for this adjustment is approximately 15 minutes which would add approximately 10 dollars to the price of the equipment.

5.1.4 Conclusions. With accuracies of $\pm$7.5 degrees and peak accuracies of $\pm$45 degrees, the open loop compass would have situations where communication would be seriously impaired. Even though it might be brief, the user would be disconcerted with these outages. In some cases, the pointing accuracy to the satellite will require greater pointing accuracy than that obtained with the compass to provide a high degree of isolation.

5.2 Antenna Pointing Through Use of AGC. The receiver AGC provides a measure of signal strength at the receiver. The receiver signal strength varies as a function of multipath fading and antenna pointing error. The receiver AGC signal can be used as an indication of signal presence (see Figure 5.2-1). The antenna azimuth 3dB beamwidth is 20° with a 1dB beamwidth of approximately 11.5°. To develop an antenna pointing signal, an error signal for the antenna servo system must be developed. The servo control error signal ideally requires both magnitude and sign. Magnitude is required so the servo can drive rapidly for large errors or more slowly for small errors. Sign is required so the servo knows which way to drive. The AGC signal provides a low resolution magnitude signal without sign.

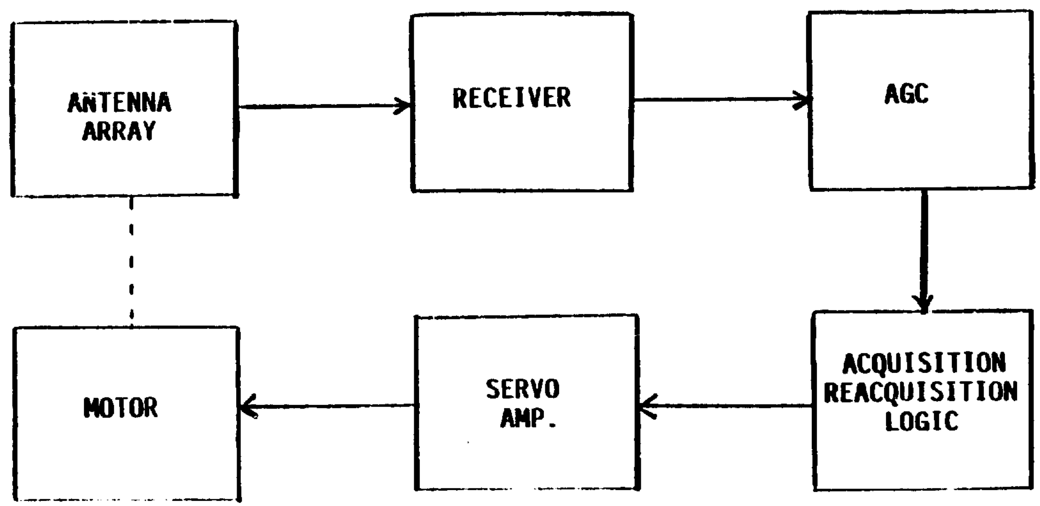


FIGURE 5.2-1

ANTENNA POINTING THROUGH USE OF AGC

Sign or direction sense can be obtained from the rate of change of AGC voltage. This can be implemented in one of two ways: dither the antenna about beam center or include a memory of last AGC voltage and antenna position. Dithering or moving the antenna about the beam center is the standard conical scan technique used in directional antennas. The need to move the antenna over a large angle before a change of signal level can be detected (1dB BW of 11.5°) makes dithering the antenna undesireable.

Use of memory is a method where signal level is sampled and stored along with a reference antenna position. If the signal level drops the antenna drives in the direction last remembered as a larger signal while taking new signal level measurements. If the signal level increases then the antenna continues moving in that direction. If the signal level decreases the antenna reverses direction and seeks out the point at which the largest stored value was obtained. This procedure might be described as a low, digital dither.

The use of AGC as an antenna pointing signal results in some problems:

Signal strength is a function of multipath fading as well as antenna pointing accuracy. When using AGC alone for antenna control, the control loop cannot separate signal fading from antenna pointing error. This could confuse the control signal sign, direction of error correction, and lead to loss of the signal during vehicle turns.

The wide beamwidth and low sensitivity of the antenna control loop could result in low pointing accuracy. While a 6° pointing error results in only a -1dB (20 percent) reduction in receive signal power, the pointing error significantly reduces the antenna isolation between adjacent satellites. Table 5.2-1 and 5.2-2 summarizes the advantages and disadvantages for both AGC and compass aided AGC tracking.

TABLE 5.2-1

ANTENNA AZIMUTH

ANTENNA POINTING USING RECEIVER AGC

ADVANTAGES

- LOW COST

DISADVANTAGES

- LOW ACCURACY ($\pm 6°$ at ± 1 dB)
- LONG ACQUISITION (16.4 sec)
- POTENTIAL INCREASED ERROR/LOSS OF LOCK UNDER MULTIPATH, SIGNAL FADING CONDITIONS.
- RECEIVER INTERFACE CONSTRAINTS: LINEAR AGC, ETC.
- NO SIGN SENSE TO ANTENNA SERVO.
- DECREASED ISOLATION TO ADJACENT SATELLITES DUE TO LOW ACCURACY.
- POTENTIAL FOR FALSE LOCK ON WRONG SATELLITE.

TABLE 5.2-2

ANTENNA AZIMUTH

ANTENNA POINTING USING MAGNETIC COMPASS AND RECEIVER AGC

ADVANTAGES

- LOW COST
- FAST ACQUISITION
- REDUCED PROBABILITY OF FALSE LOCK ON WRONG SATELLITE (compared to AGC sensing alone)

DISADVANTAGES

- LOW ACCURACY ($\pm 6°$ AGC @ ± 1 dB, $\pm 7.5°$ COMPASS)
- DECREASED ISOLATION BETWEEN ADJACENT SATELLITES DUE TO LOW ACCURACY.
- RECEIVER INTERFACE CONSTRAINTS: LINEAR AGC, ETC.
- POTENTIAL INCREASED ERROR DUE TO SIGNAL SHADING, MAGNETIC ANOMALIES, SIGNAL FADING.

5.3 Pseudomonopulse Tracking. Figure 5.3-1 shows a block diagram of the pseudomonopulse system. A 180-degree hybrid is used to produce a sum and difference radiation pattern as shown in Patterns 5.3-1 and 5.3-2. The difference signal is attenuated by means of a coupler and added and subtracted to the sum channel. (The result is shown in Figure 5.3-1.) This signal results in a slight amplitude modulation to incoming RF signal. The RF signal is down converted and amplified at intermediate frequency. A simple diode detector used for AGC detects the modulation and the reference modulator is phased detailed with the modulation resulting in a typical error "S" curve, the error voltage being proportional to angle from the main beam. Features of this system are:

- No AM is present when the antenna is boresighted on target.
- The AM modulation can be at any frequency within channel bandwidth as long as there is no interference with the FM data channel.
- The antenna is pointed accurately to the satellite.
- This system is simple and requires little interface to the receiver.

The tracking accuracy of this type system is typically 0.5 degrees based on the error slope and noise in the tracking bandwidth. An important feature of this system is its ability to track substantially below the noise floor of the data channel. This occurs because the information bandwidths are different. Table 5.3-1 and 5.3-2 show the tradeoffs. Figure 5.3-2 is a block diagram of a pseudomonopulse receiver. Figure 5.3-3 shows the acquisition, reacquisition, and tracking logic.

5.3.1 Monopulse Switching Frequency Considerations. There has been concern that the monopulse AM could interfere with the data signal in one of the following ways:

1. Interfere with the data channel demodulation.
2. Interfere with the adjacent channel.
3. Cause PLL false lock.

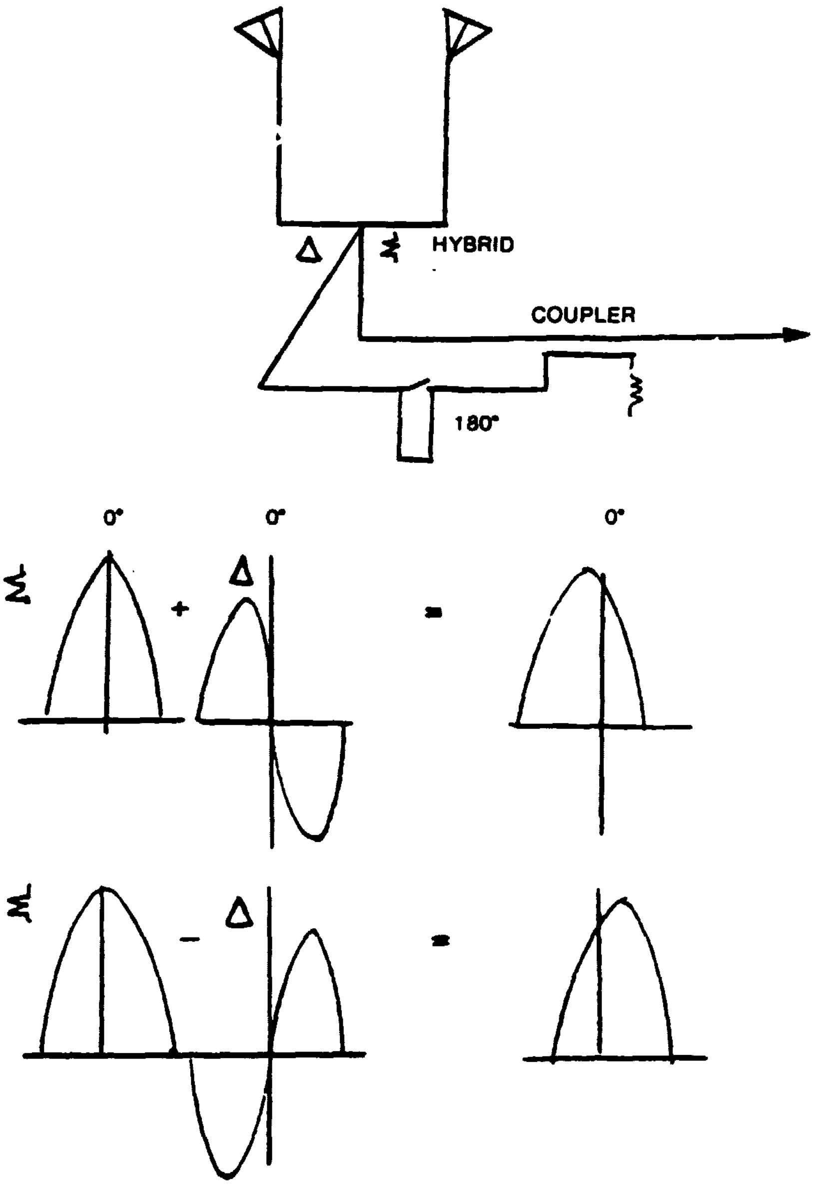
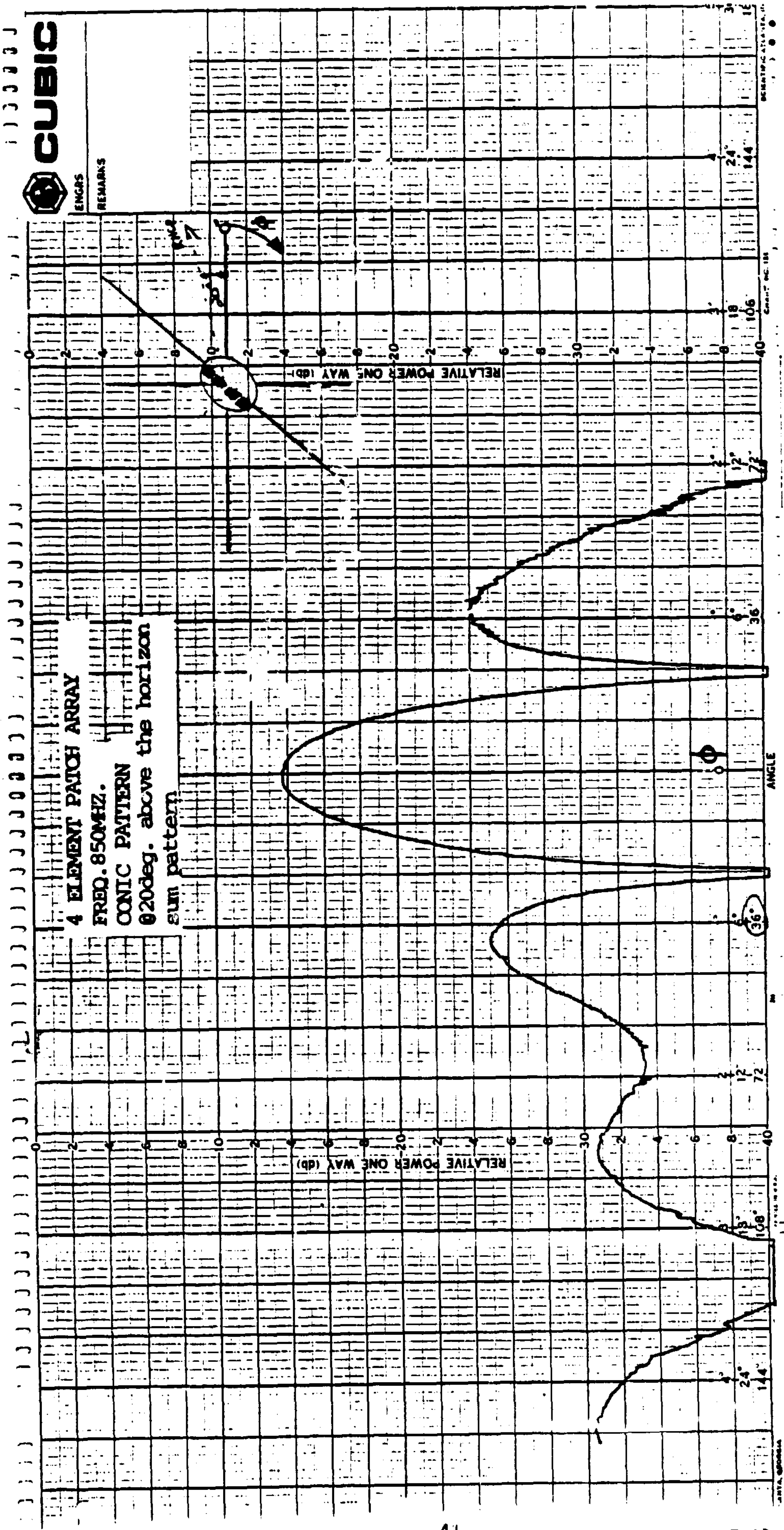


FIGURE 5.3-1
PSEUDOMONOPULSE TRACKING



PATTERN 5.3-1

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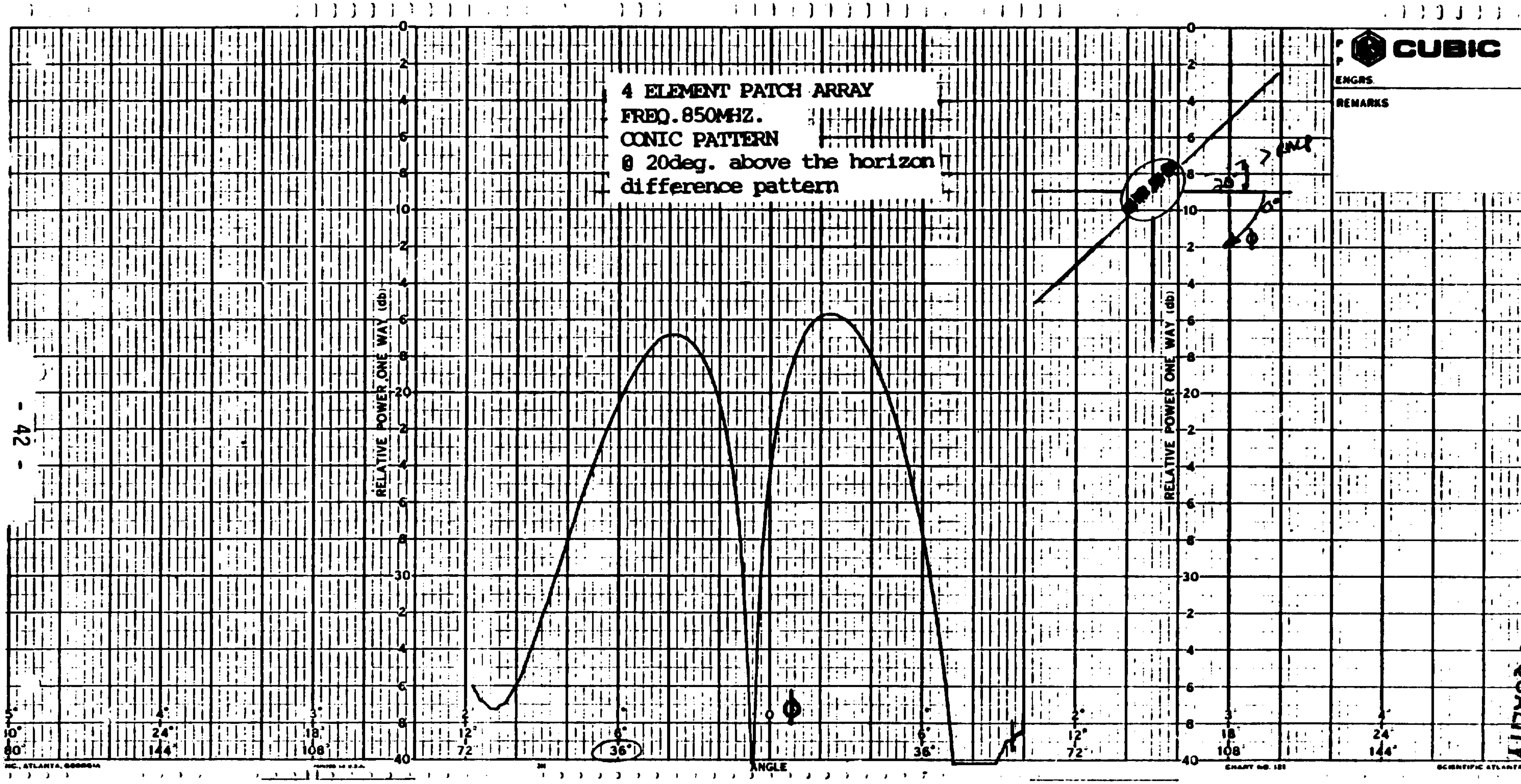

PATTERN 5.3-2

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TABLE 5.3-1

ANTENNA AZIMUTH

MONOPULSE TRACKING ANTENNA TRADEOFFS

ADVANTAGES

- REQUIRES NO OPERATOR INPUTS EXCEPT ON/OFF CONTROL
- HIGH ACCURACY TO RECEIVER THRESHOLD $\leq$ BW/10
    - Pointing accuracy independent of latitude or direction
    - Uniform, stable servo characteristics
    - Pointing accuracy independent of stray magnetic fields
    - Accuracy relatively independent of installation
    - Accuracy relatively independent of normal vehicle motion or vehicle attitude
    - Improved isolation to adjacent satellites due to high accuracy.

TABLE 5.3-2

ANTENNA AZIMUTH

MONOPULSE TRACKING ANTENNA TRADEOFFS

DISADVANTAGES

- Search required for initial signal acquisition
  - Acquisition time can be as long as 15 seconds depending upon servo, SNR, and initial pointing error.
  - Reacquisition required after signal dropout (travel through tunnel, past large buildings)
  - Acquisition/reacquisition time increased by detector acquistion time.
- Antenna losses introduced.
  - Sum path includes a hybrid and coupler.
- Antenna design for Σ and Δ signals more complex than magnetic pointed receiving antenna.
- An integrated data receiver/monopulse tracking receiver is optimum. Interfaces must be coordinated.

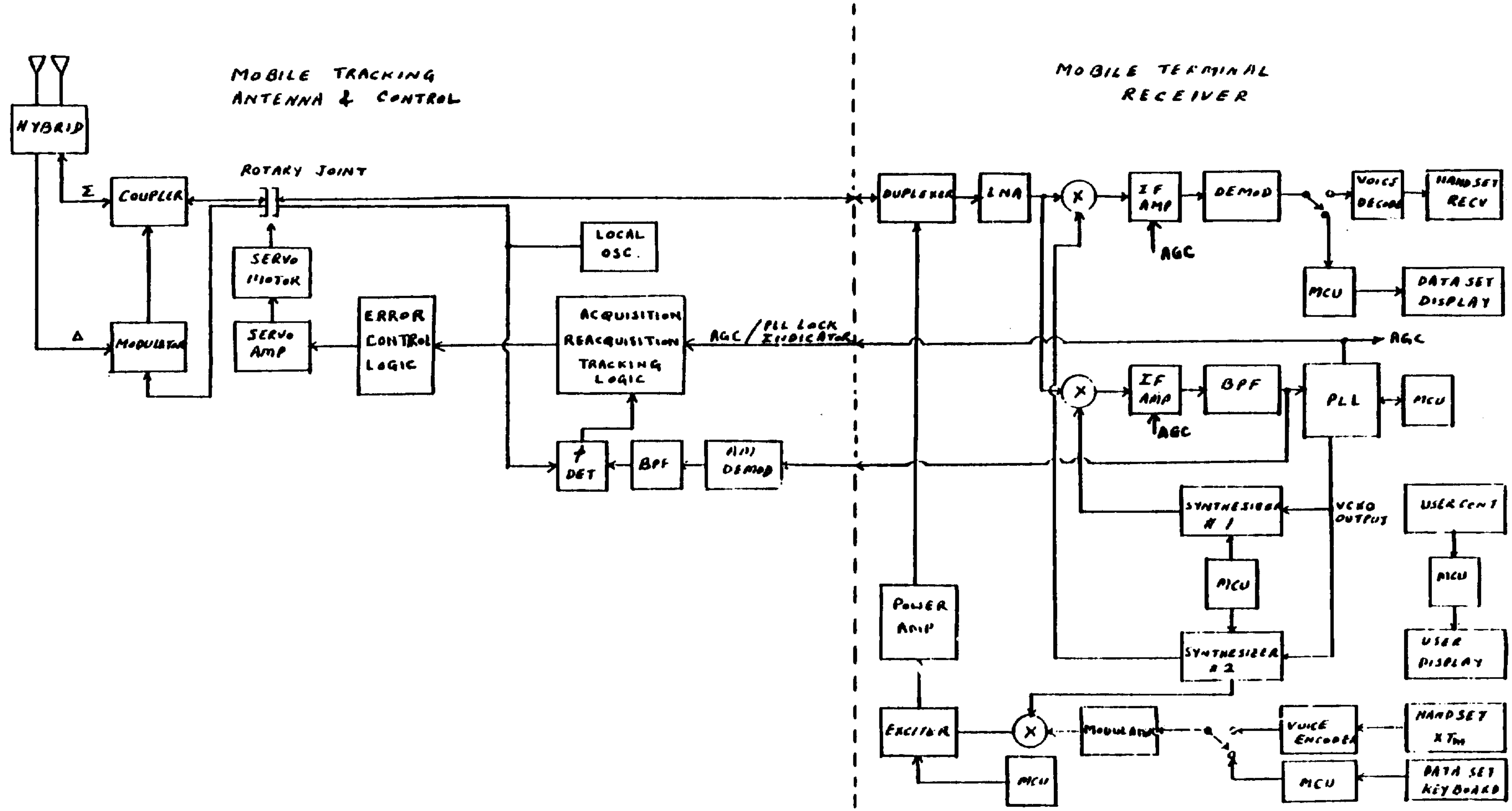

FIGURE 5.3-2. PSEUDOMONOPULSE RECEIVER

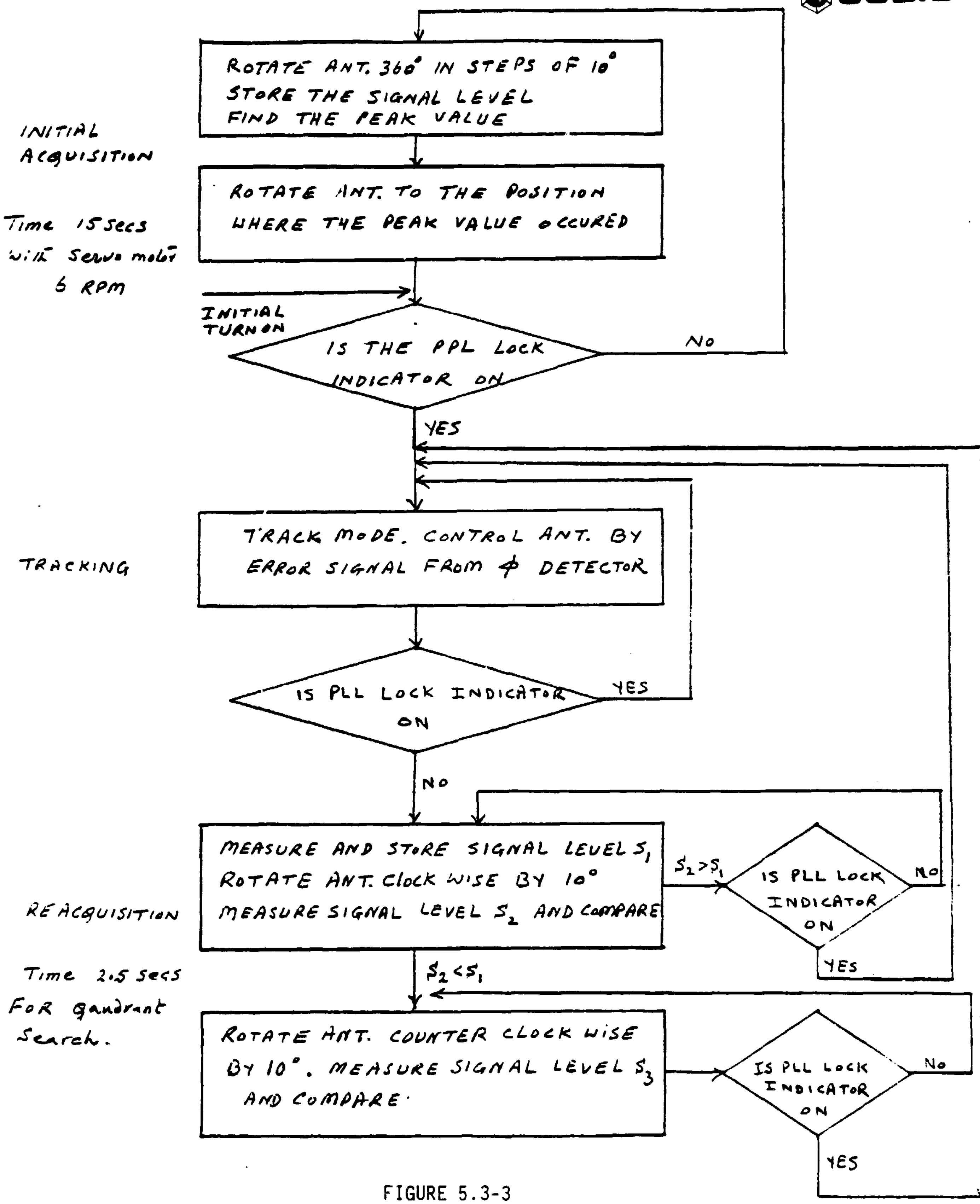

FIGURE 5.3-3
MONOPULSE RECEIVER ACQUISITION AND REACQUISITION
AND TRACKING SEQUENCE FLOW DIAGRAM

5.3.1.1 Data Channel Demodulation. If the data channel is an FM/PM modulated signal then the demodulator should not see the small AM modulation resulting from the antenna tracking signal. The AM would be observable only during antenna acquisition when data transmission is unlikely. The AM modulation would be negligible in comparison to the AM modulation resulting from signal fading received at a moving vehicle.

Any tracking signal aM at the input of an FM/PM demodulator can be eliminated by using a limiter ahead of the demodulator and thus have no effect on the demodulator. If the data modulation includes AM then amplitude monopulse can still be used using one of two techniques:

(1) Frequency division multiplexing - the monopulse signal is a narrow band fixed frequency signal. It can be placed at the data band edge of the data AM modulation.

(2) Separate difference channel receiver - if the full data channel is used for AM modulation then a separate difference channel receiver can be used. (See block diagram)

5.3.1.2 Adjacent Channel Interference. It has been commented that the AM modulation might cause adjacent channel interference. This can be prevented by the following design considerations:

(1) A mixer with an input frequency f_1 and LO frequency f_2 can have outputs of $\pm Mf_1 \pm Nf_2$. By proper choice of LO frequency f_2 and a bandpass filter at $(f_1 - f_2)$ all products of M and N greater than 1 of significant magnitude will be rejected. This would include the AM modulation frequencies $(f_1 \pm f_m)$.

(2) A mixer with multiple frequency signal inputs can have third order, two tone products. An AM spectrum actually has three tones f_1, $f_1 + f_m$, and $f_1 - f_m$. Use of a class III mixer minimizes two tone products. The Watkins-Johnson catalog gives relative two tone - third order IMD outputs of -106 dBm down for two input signals at -18 dBm using an M9D mixer, thus IMD can be minimized by choice of mixer.

(3) By keeping the pseudomonopulse modulation frequency low, any harmonic product frequencies are low. If the channel bandwidth is 5 kHz, the monopulse modulation frequency is 833 Hz or less, then third order products cannot reach the adjacent channel.

5.3.1.3 PLL False Lock. If the antenna is on the peak difference lobe, the PLL is in the acquisition mode, and the PLL has sufficient sensitivity then it might be possible for the PLL to lock to the $f_1 \pm f_m$ frequency term. The input frequency uncertainty is expected to be approximately 200 Hz. If the PLL acquisiton frequency range is limited to ±100 Hz and f_m is greater than 100 Hz then PLL false lock cannot occur.

5.3.2 SNR Versus Tracking Error. RMS tracking error given by:

$$\sigma_t = \frac{\theta}{K_m \left(\frac{S}{N} \quad \frac{\beta}{\beta_s} \right)^{\frac{1}{2}}}$$

σ_t is RMS tracking error degrees.

θ is beamwidth degrees

$\frac{S}{N}$ is IF SNR

β is IF bandwidth

β_s is servo loop bandwidth

K_m is normalized error slope of Δ pattern ≈ 1.2

Assume desired tracking error = 0.1 x beamwidth = 2°

$$\left(\frac{S}{N} \bullet \frac{\beta}{\beta_s}\right) = \left(\frac{\theta}{\sigma_t K_m}\right)^2 = \left(\frac{10}{1.2}\right)^2 = 69.44$$

$$\left(\frac{S}{N}\right) IF_{dB} + \left(\frac{\beta}{\beta_s}\right) dB = 18.4 \text{ dB}$$

Given β = 5 kHz IF bandwidth

SNR at IF required to obtain σ_t/θ = 0.1 is given for various values of servo bandwidth B.

β_s	(S/N) IF dB
1 Hz	-18.6
2 Hz	-15.6
4 Hz	-12.6
5 Hz	-11.6

This analysis assumes no loss in the AM detector. However at such low SNR, a non-coherent AM detector will be below threshold showing a loss of about 5 dB. Thus the system will track at -13.6 dB SNR with 1 Hz servo bandwidth. The SNR required for data demodulation is +11 dB showing a differential of 24.6 dB.

The acquisition of the proper satellite with the monopulse system can be done in several ways. Each is dependent on the design of the transceiver and satellite transceiver. The easiest is having each satellite dedicate a portion of one channel as an identification channel. The preferred satellite is then selected from transceiver front panel. It may be that each satellite is implemented by different industrial organizations offering different classes of service tailored to the protocals of its own gateway and telephone system making the user prefer one satellite to another. Also, different classes of service may be offered because of regional marketing circumstances.

The auto driver may elect which class of service he desires. This would make satellite identification very desirable. It may be he has an optional one polarization antenna so he has to choose the right satellite. For these systems the AGC would be suppressed so the antenna would slew to the correct satellite. For a 6 rpm servo the antenna would acquire in 10 to 15 seconds. Reacquisition (within one beamwidth) would require 1.3 seconds.

In the case where there is no satellite identification code, the antenna would always slew clockwise. The scenario would be (1) loss of lock, (2) the antenna slews greater than 40 degrees and then starts counting AGC pulses. The most Easterly satellite would be the first pulse, mid-continent the second, and most Westerly, the third. The antenna is programmed to stop near the appropriate satellite and the tracking loop closed. If the antenna stopped within seven degrees of the correct satellite, the loop would close and the antenna would track. For a 6 rpm servo the antenna would acquire in 10-15 seconds and reacquire in a beamwidth representing 1.3 second. If the AGC drops below a given threshold the antenna re-acquires by rotating a full turn and counting AGC levels again.

5.4 Pseudomonopulse - Compass Aided. The block diagram of a compass aided system is shown in Figure 5.4-1. Compass aided tracking provides continuous antenna pointing regardless of multipath fading, gain, under underpasses and blockage from foliage. Figure 5.4-2 shows the acquisition and tracking logic. Table 5.4-1 summarizes the trade offs. The pointing uncertainty, however, led to ideas of accelerometers and eventually to rate gyro aided pointing.

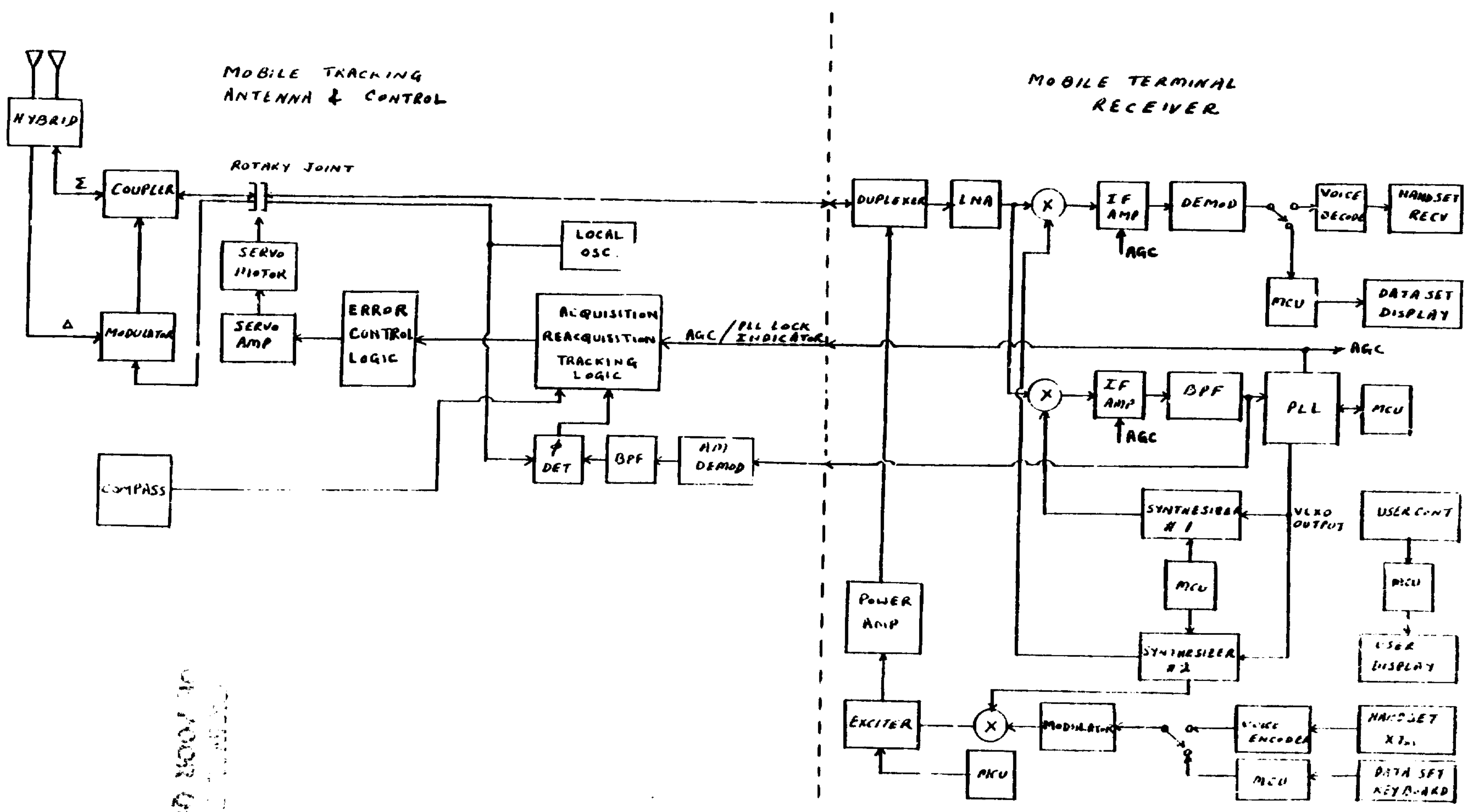

FIGURE 5.4-1
PSEUDOMONOPULSE RECEIVER COMPASS AIDED

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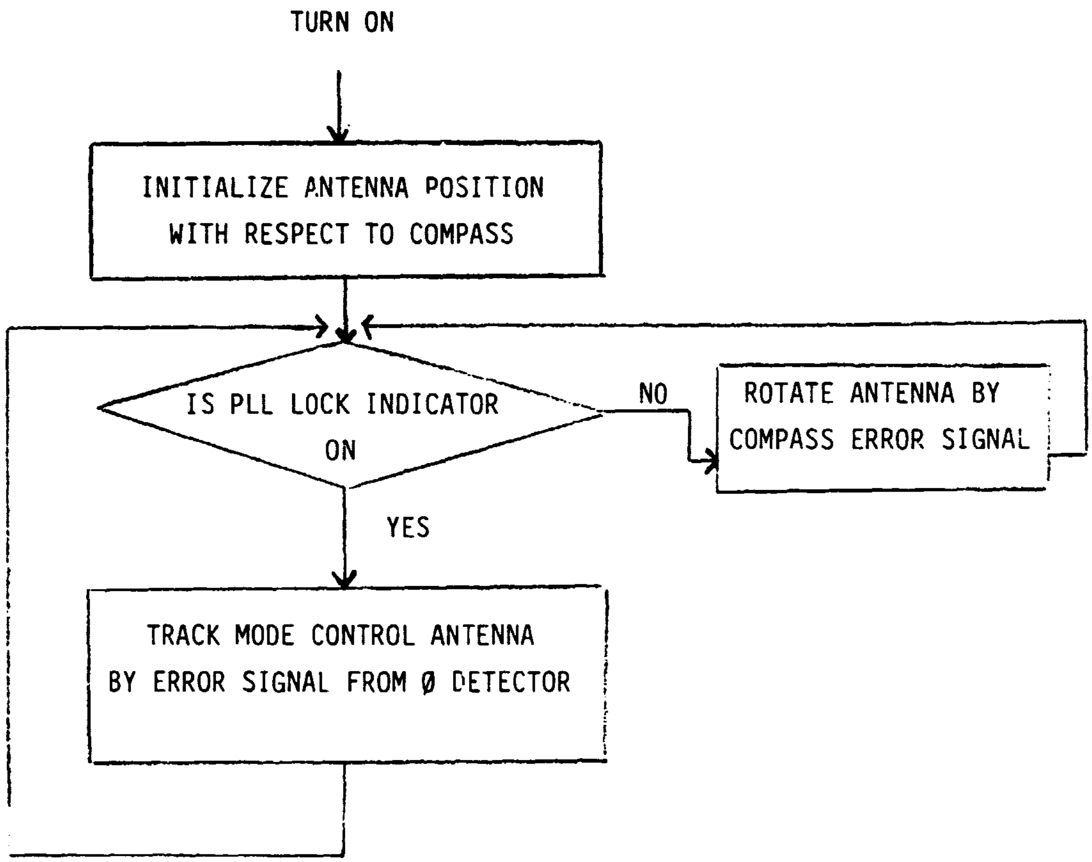

MONOPULSE RECEIVER AIDED BY COMPASS ACQUISITION
AND TRACKING SEQUENCE
FLOW DIAGRAM

FIGURE 5.4-2

TABLE 5.4-1
ANTENNA AZIMUTH
COMPASS AIDED MONOPULSE TRACKING ANTENNA TRADEOFFS

ADVANTAGES

ALL THE ADVANTAGES OF AN UNAIDED MONOPULSE RECEIVER PLUS:

- REDUCED MAXIMUM ACQUISITION TIME (5.1 SECONDS VERSUS 15.1 SECONDS AT 6 RPM SERVO).
- SMALL TO NEGLIGIBLE REACQUISITION TIME UNDER MOST ($\approx$95%) CIRCUMSTANCES.

DISADVANTAGES

- ADDITIONAL COST ($\approx$ \$10)
- POSSIBILITY OF COMPASS ERROR DURING ACQUISITION GREATER THAN BEAMWIDTH, SLOWING ACQUISITION.
- INTEGRATION, COMPLEXITY, COST FACTORS OF A MONOPULSE RECEIVER.

5.5 Pseudomonopulse - Rate Gyro Aided. A simple low cost rate gyro was found. The rate gyro output is angular rate. By integrating the rate, the angular position is obtained. Feeding this angular position to the antenna servo when loss of lock occurs the antenna will slew back to the position prior to the loss of signal. A block diagram of this system is shown in Figure 5.5-1. Table 5.5-1 summarizes the tradeoffs. A photo of the gyro is in Figure 5.5-2. The gyro consists of a motor, two flywheels, a small magnet, and a Hall effect diode. The output is bipolar with CW and CCW directions. The gyro was placed on a turntable and the rate varied. The output of the gyro and amplifier is a DC level proportional to angular rate as shown in Figure 5.5-2.

5.6 Monopulse Separate Receiver. An alternate monopulse system using a separate receiver is shown in the Block Diagram of Figure 5.6-1. The advantage is that there is no data transfer from receiver to antenna integration or connection but since a separate receiver is used, the system becomes expensive. Assuming the transceiver cost $1500 and half the cost is in the transmitter, the antenna cost will increase approximately $750.

5.7 Servo Design. Since the size of the motor drive is a critical part of the cost, the moment of inertia was calculated. A motor torque requirement of 75 oz.in. was calculated for 25°/sec acceleration. A very small motor of undetermined torque but of very low cost was used to edge drive the 26-inch ground plane of a dynamic antenna mockup. It was clear from this demonstration that small inexpensive motors may be used to steer the antenna. A motor of the required torque can be purchased for $7.50 each in large quantitites. A preliminary schematic diagram of the servo system was sketched for the pseudomonopulse system and is shown in Figure 5.7-1.

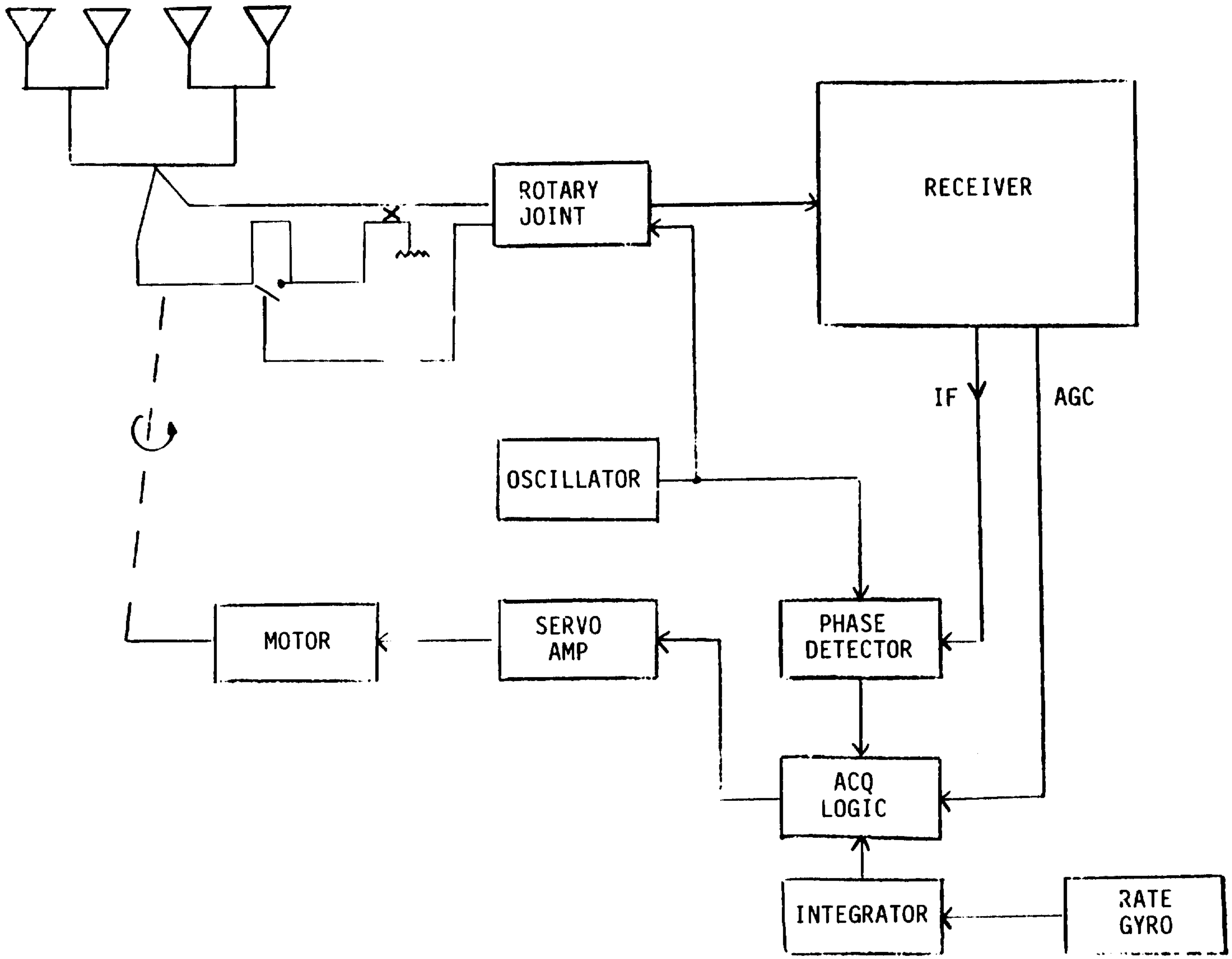

FIGURE 5.5-1
PSEUDOMONOPULSE - RATE GYRO AIDED

TABLE 5.5-1
ANTENNA AZIMUTH
RATE GYRO AIDED MONOPULSE TRACKING ANTENNA TRADEOFFS

ADVANTAGES

ALL THE ADVANTAGES OF AN UNAIDED MONOPULSE RECEIVER PLUS:

- DIRECTION HOLD UNDER SIGNAL DROPOUTS SHOULD RESULT IN NEGLIBIBLE REACQUISITION TIME INDEPENDENT OF SIGNAL SHADING, MAGNETIC ANOMALIES, OR VEHICLE MANEUVERS.

DISADVANTAGES

- ADDITIONAL COST ($\approx$ \$15)
- NO REDUCTION IN INITIAL ACQUISITION TIME ($\approx$ 15 SECONDS)
- INTEGRATION, COMPLEXITY, COST FACTORS OF A MONOPULSE RECEIVER.

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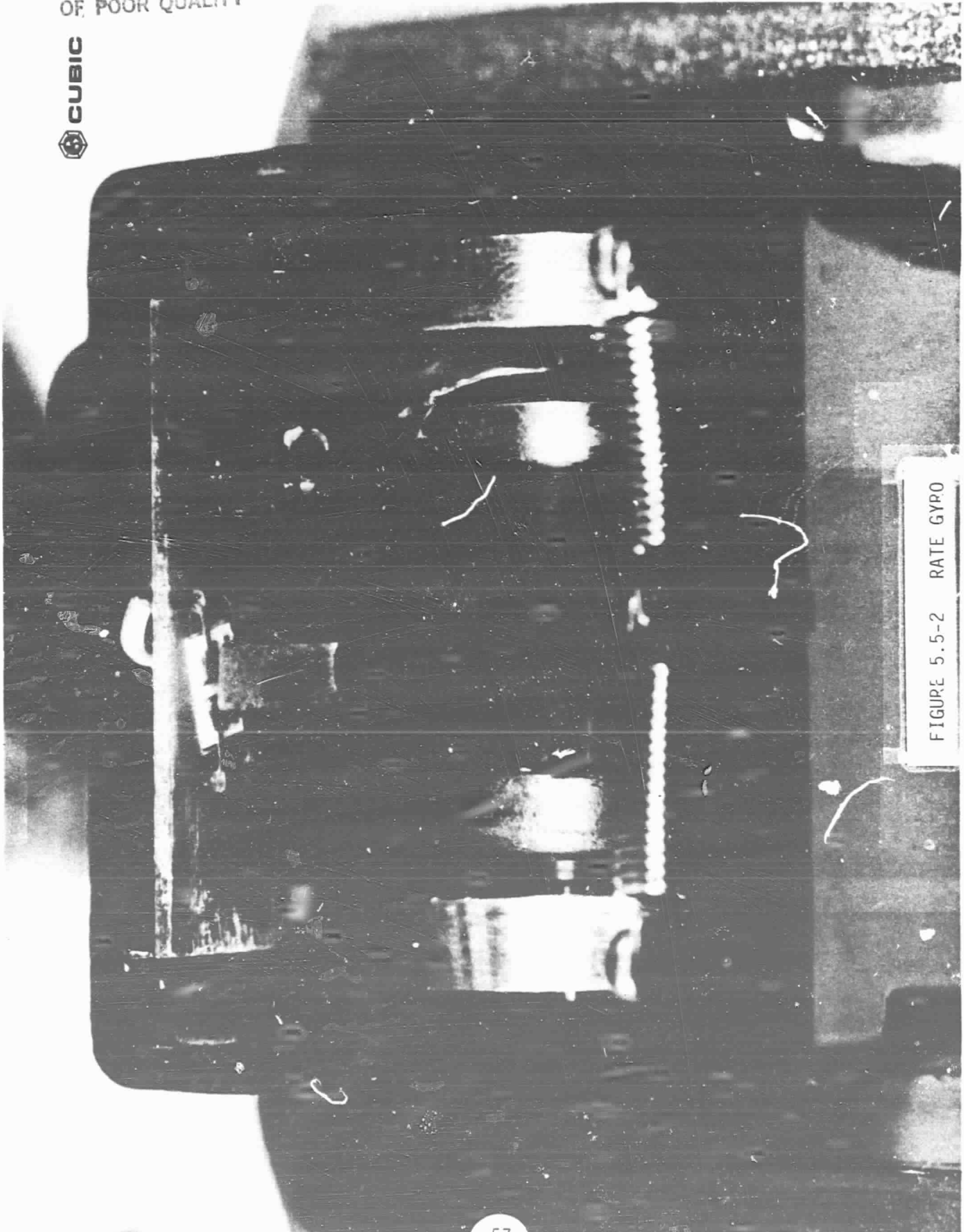

FIGURE 5.5-2 RATE GYRO

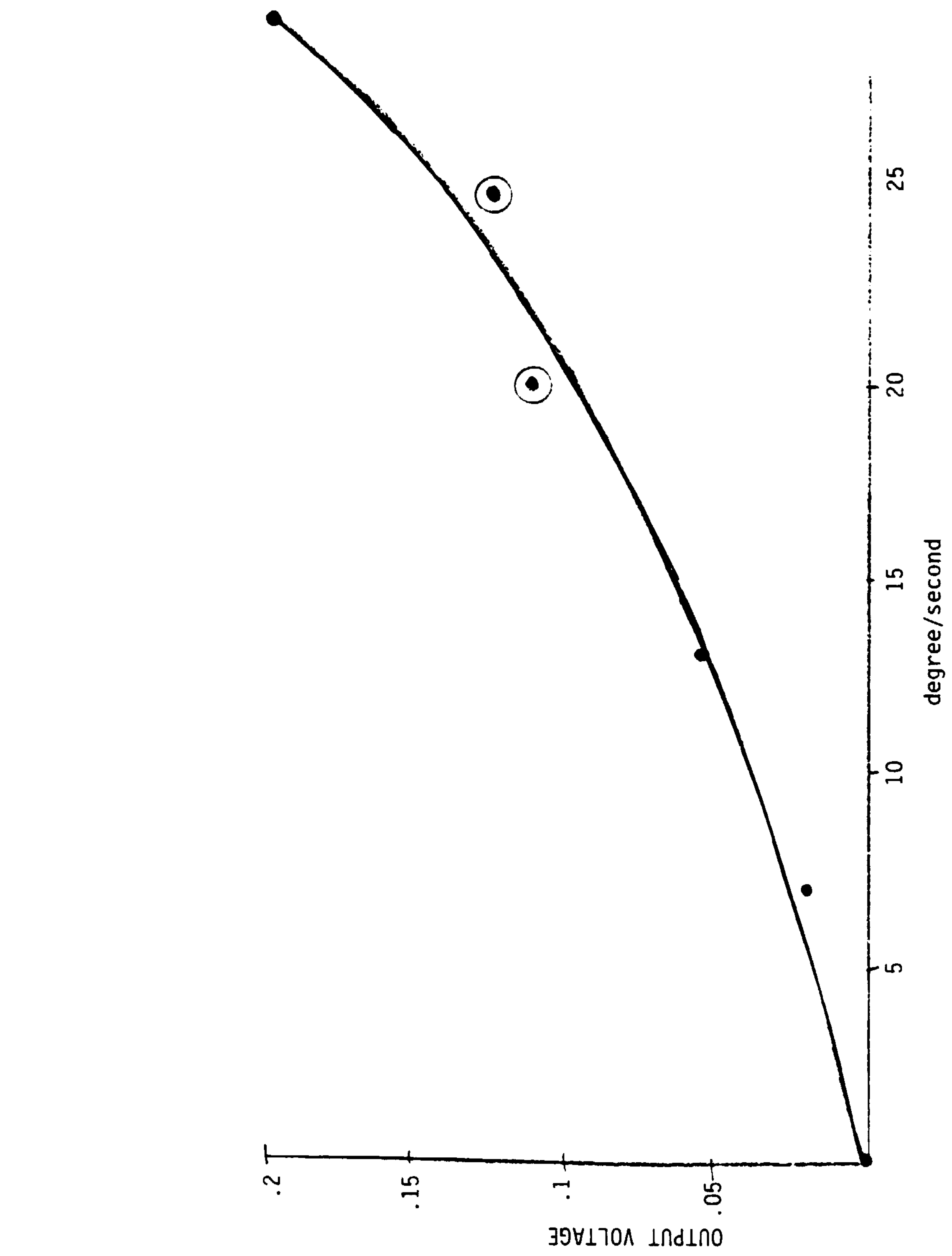

FIGURE 5.5-3. RATE GYRO OUTPUT

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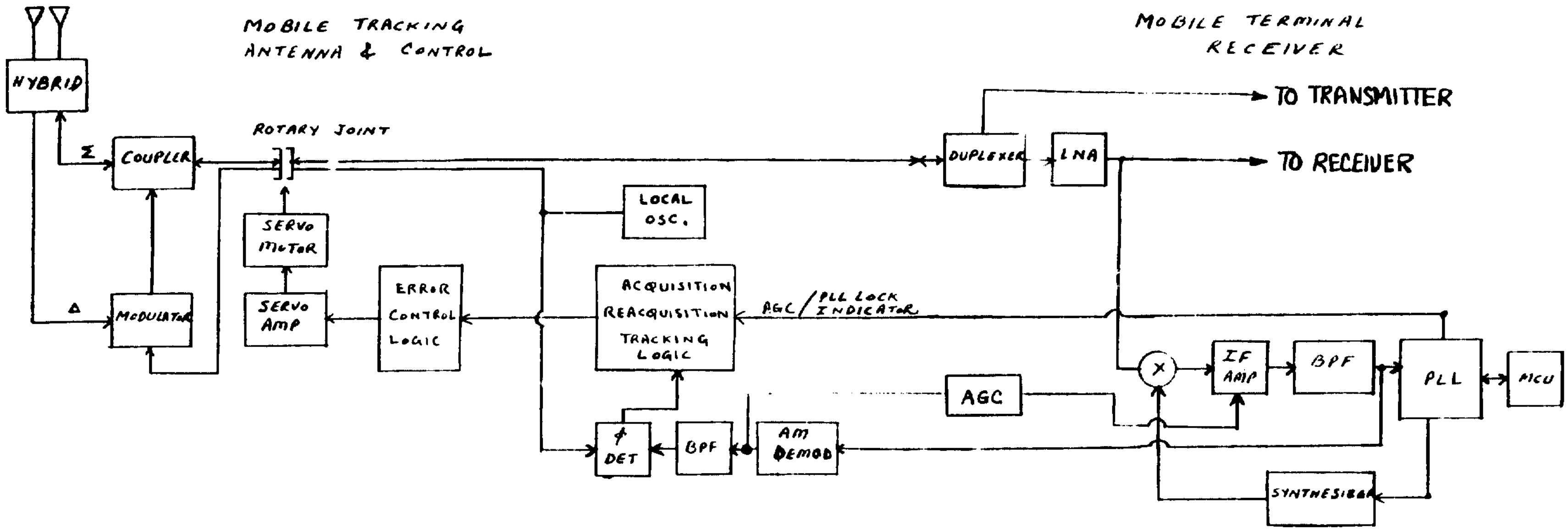

FIGURE 5.6-1
SYSTEM WITH SEPARATE RECEIVERS

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NOTES: UNLESS OTHERWISE SPECIFIED

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APVD

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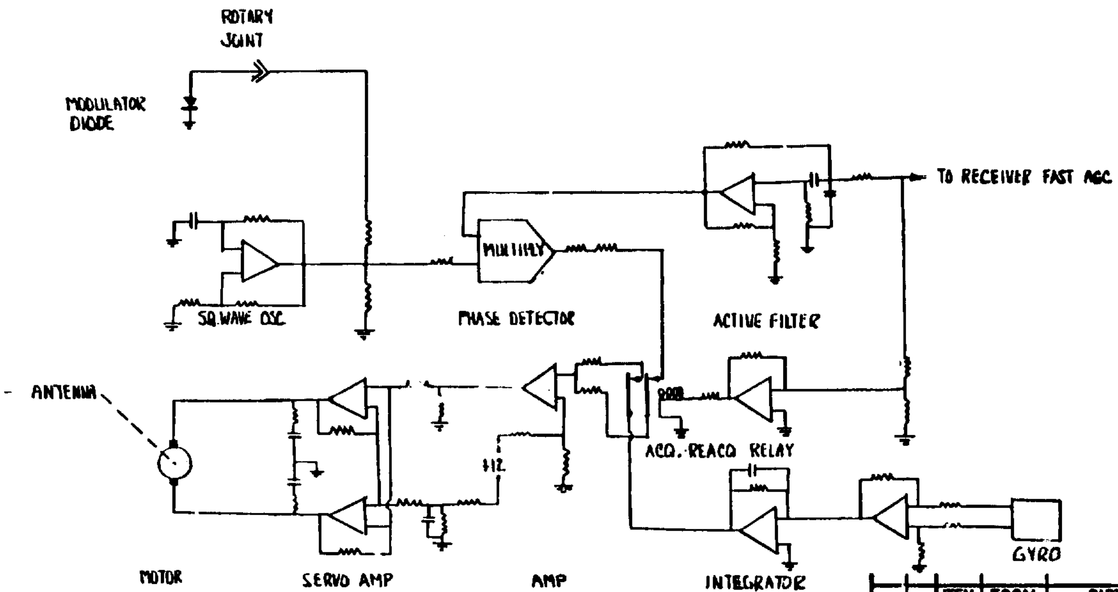

FIGURE 5.7-1
PRELIMINARY SCHEMATIC

QTY PER ASSY	ITEM NO.	FSCM NO.	PART OR IDENTIFYING NO.	DRAWING OR SPECIFICATION	NOMENCLATURE OR DESCRIPTION	MATERIAL	NOTE NO

PARTS LIST

UNLESS OTHERWISE SPECIFIED LINEAR DIMENSIONS ARE IN INCHES TOL ON DECIMALS .XX ± .03 .XXX ± .010 ANGLES ± 30'

UNLESS OTHERWISE SPECIFIED HOLE TOLERANCES ARE:

HOLE DIA	TOLERANCES
.0136 THRU .125	+.004 -.001
.126 THRU .250	+.005 -.001
.251 THRU .500	+.006 -.001
.501 THRU .750	+.008 -.001
.751 THRU 1.000	+.010 -.001

CONTRACT NUMBER

REL
MAINT
STD
ENGRG
DESIGN
CHECK
DRAWN

DESIGN ACTIVITY APPROVAL

APPROVED

CUBIC CORPORATION
Defense Systems Division
9233 BALBOA AVE.
SAN DIEGO, CA. 92123

SCHEMATIC DIAGRAM LMSS (X)

SIZE	CODE IDENT NO	DRAWING NUMBER	REV
C	94987		

SCALE | SHEET | OF

REV	DASH NO.	NEXT ASSY	PART NO.	SER NO.

APPLICATION | USED ON

SH. 7	SH. 8	SH. 9	SH. 10	SH. 11	SH. 12
SH. 1	SH. 2	SH. 3	SH. 4	SH. 5	SH. 6

REV STATUS OF SHEETS

6.0 COSTING

The 1x4 mechanically steered array was priced for 10,000 and 100,000 units using the gyro aided pseudomonopulse system. The fabrication cost was quoted by the Cubic production facility for the antenna. The electronics package was priced using the RCA cost model computer program. All costs are based on 1983 dollars with a manufacturing period of 36 months and do not include profit. The optimum production time frame for the electronics package is twelve months. However, in a commercial environment, production rate will be controlled by the market. The detail breakdown is in Figure 6.0-1. The fabrication techniques are highly productionized so that there is little intensive labor involved. The use of a foreign manufacturer will reduce the price approximately 100 dollars. The percentage breakout is 50 percent antenna and 50 percent electronics. The antenna fabrication costs do not differ appreciably from 10,000 to 100,000 units, however, the electronics package will drop from \$184 to \$121 each. The price reduction over previous quotes is about 50 percent since the electronics package has been added to the antenna cost in this effort.

The cost of the mechanically steered conformal antenna is shown in Figure 6.0-2. The reduction in cost from the previous data represents the elimination of expensive phase shifters. The electronics package for the pseudomonopulse and motor drive being added to the antenna costs in this phase raised the cost slightly. Figure 5.7-1 is a preliminary schematic of the electronics package priced as part of the antenna system. The motor included is a 12 V DC permanent magnet type which at 3700 rpm with a 80 gcm torque draws .5 amps. Breadboard and prototype costs are included in Table 1.0-1. These prices include acceptance testing. Antenna patterns, tracking verification in an antenna range environment and testing under environmental conditions are

FIGURE 6.0-1

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE ____ OF ____

PROPOSAL LINEAR ARRAY 10,000 and 100,000 UNITS PREPARED ____ DATE ____

PROPOSAL ITEM ____ MQ. NO. ____ APPROVED ____ DATE ____

QUOTE NO. ____ APPROVED ____ DATE ____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT DOLLARS
1	DK1100205	40K	SUPPORT	7,000							21
2	DK1100202	10K	BASE	23,0CO							37
3	DK1100201	60K	BRACKET	225,000							22.5
4	RADIATOR ASSY.	10K			2,138.2	1,139.4			15,238	1.851	74
5	TOOLING										2
6	ELECTRONICS										184 (121)
7	ROTARY JOINT										75
8	WAVEGUIDE		TOOLING 15,000 $ 2 ea.								3.5
9	MOTOR										7.5
10	GYRO										25
11	CABLE TOOLING		12,579								12.5
12	RADOME										35.
	TOTAL										$499 * $436 **

* = (10,000)   ** = (100,000)

CF 11-16-4G

FIGURE 6.0-2

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE ______ OF ______

PROPOSAL CONFORMAL ARRAY 10,000 and 100,000 UNITS PREPARED ______ DATE ______

PROPOSAL ITEM ______ MQ. NO. ______ APPROVED ______ DATE ______

QUOTE NO. ______ APPROVED ______ DATE ______

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS					TOTAL HOURS (UNIT)	UNIT DOLLARS
					CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU		
	FAB. PARTS										413
	. RADIATOR ASSY										
	. SUPPORT										
	. GROUND PLANE										
	STRUCTURE										
	RADOME										35
	MATERIAL										185
	ELECTRONICS										184 (121)
	ROTARY JOINT										75
	MOTOR										15
	GYRO										25
	CABLE TOOLING										12.5
	TOTAL										$944 * $881 **

* = (10,000) ** = (100,000)

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included. However, more extensive testing procedures are being considered, and any proposal effort would include more extensive discussions of the testing requirements. Table 6.0-1 is a cost comparison summary of the various pointing options presented in this report.

TABLE 6.0-1
ANTENNA BEAM POINTING

SUMMARY COMPARISON TABLE

POINTING METHOD	MAXIMUM (1) ACQUISITION TIME (sec)	REACQUISITION TIME (sec)	ACCURACY TIME TYPICAL	ACCURACY TIME PEAK	ROBUSTNESS @ FADING, SHADOWING	QUANTITY COST ESTIMATE, $ (3)	COMMENT
MAGNETIC COMPASS	5.1	N/A	$\pm 7.5°$	$\pm 45°$	N/A (2)	$454	(4)
RECEIVER AGC	16.4	16.4	$\pm 6.0°$	$\pm 10°$	Poor	$454	(4)
AGC and COMPASS	6.3	1.3	$\pm 6.0°$	$\pm 10°$	Fair	$464	(4)
UNAIDED MONOPULSE	15.1	10.1	$\pm 0.5°$	$\pm 2°$	Good	$474	
COMPASS AIDED MONOPULSE	5.1	N/A	$\pm 0.5°$	$\pm 2°$	Good to Excellent	$484	
RATE GYRO AIDED MONOPULSE	15.1	N/A	$\pm 0.5°$	$\pm 2°$	Excellent	$499	

NOTES:
(1) ACQUISITION TIME BASED ON A 36°/SEC (6 RPM) MAXIMUM SERVO RATE.
(2) COMPASS SENSOR IS INDEPENDENT OF PROPAGATION CONDITIONS.
(3) ESTIMATED QUANTITY COST OF ANTENNA AND BEAM POINTING ASSEMBLY (10,000 unit).
(4) NOT RECOMMENDED FOR MULTIPLE SATELLITE USE DUE TO LOSS OF ISOLATION WITH LARGE POINTING ERROR.